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Carr, Donald Stephen

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AN ANALYSIS OF MARINE PROPULSORS AND THEIR APPLICATIONS

DONALD STEPHEN CARR

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AN ANALYSIS OF MARINE PROPULSORS

AND THEIR APPLICATIONS

by

Donald Stephen Carr
Major, United States Marine Corps
B. S., College of the Holy Cross, 1955

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
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1967
CARR, P.
c. [redacted]

ABSTRACT

Increased interest on the part of the United States in the exploration and exploitation of the ocean environment has led to the assignment of diverse missions in this field to the military. Development of numerous vehicles and weapons systems and the propulsion units to propel them is required to accomplish these missions. In this paper, a general classification of propulsors is established and important performance parameters are defined. A variety of marine thrust devices is described and analyzed in detail, and a qualitative comparison of performance is made. General guidelines are offered for mating propulsors and vehicles for appropriate applications and particular mission requirements. The importance of drag reduction is recognized and various techniques are discussed in an appendix. Since this paper is intended to serve as a compendium on marine propulsors, an extensive bibliography has been incorporated.

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CHAPTER 1

RECENT TRENDS IN OCEAN TECHNOLOGY

Within the preceding decade, our knowledge of the environment under the ocean surface has increased at an astounding rate. Prior to the late 1950's, minimal funds were allocated for the purposes of research and experimentation in the field of marine technology. As a result, only limited scientific efforts were devoted to the task of advancing the national awareness to the immense potential, both industrial and military, existing in the surrounding waters. The bulk of scientific expenditures, in both the personnel man-hour sense and the financial aspect, were being utilized in outer space-oriented endeavors. Very little importance was attached to the sea, a medium constituting 70 per cent of the earth's surface and containing 80 per cent of life on this planet.

Perhaps it was the tragedy of the Thresher, or the near-catastrophic experience with the lost hydrogen bomb off the coast of Spain, which brought about the most recent spurt in the development of the ocean sciences. Regardless of the immediate cause for concern, it is a fact that within the short span of ten years tremendous expansion has resulted in oceanic research efforts and in the design and development of surface and sub-surface systems. As the richness and security of the underwater environment are more fully comprehended and realized, it is conceivable that the present status of space and ocean studies will be reversed, with the primary efforts of the scientific community being centered on the development of ocean technology.

1.1 NATIONAL PURPOSE AND OBJECTIVES

The intensive efforts of the government of the United States to develop modern operational undersea and surface weaponry, to attain a higher national level of education in the field of oceanography, and to update technical knowledge in the various marine sciences are clear indications of the significance that this country attaches to future endeavors in the seawater environment. The appointment of national committees and special scientific organizations to study both the strategic and tactical aspects of the ocean reflects the importance that our national leaders perceive in the exploitation of the so-called "inner space" of the sea. The current interest in potential living sites in subaqueous surroundings and the development of the ocean as a plentiful source of economic and military power demonstrate the national awareness of the possibility of one day existing completely in an underwater environment. The Jules Verne-type concepts of underwater habitation, which were originally considered as fantasies, are rapidly becoming realities as the upsurge of oceanographic research within the last few years has been complemented by efforts of military and industrial groups to design and develop operationally effective marine vehicles and weapons systems. According to Arata[1], the Federal Council for Science and Technology has stated that the goal of the National Oceanographic Program is "to comprehend the ocean, its boundaries, its properties, and its processes, and to exploit this comprehension in the public interest, in enhancement of our security, our culture, international posture, and our economic growth."

In conjunction with advanced research in marine systems engineering, a parallel and highly influential interest has been exhibited in the science of oceanography. The knowledge attained through the study of the geography of the ocean bottom and the related properties of the sea has presented a challenge to the engineer to develop vehicles and instrumentation that will enable the oceanographer to further expand his underwater studies. Thus, it is apparent that in order to fully exploit the natural resources and intrinsic benefits that the ocean affords, a close working relationship must exist between the technician and the explorer. As new facts become known concerning the ocean environment, they must be communicated to the engineer to assist him in his approach to marine systems design, and, simultaneously, new tools must be provided to the oceanographer to enable him to penetrate the mysteries of the ocean depths.

The exploration of outer space, with the accompanying huge expenditures of talent and resources and the uncertain results involved, may presently be replaced in national importance by the promises of economic and military security to be afforded by control of the ocean spaces. Many of the accomplishments and theoretical endeavors of the scientists and engineers in aerospace activities can be conveniently and effectively redirected to hydrodynamic applications. An excellent illustration of this fact is the projected use of fuel cells for marine propulsion systems. These energy sources were developed through aerospace technology to perform specific functions in the Apollo and Gemini missions and now, following appropriate modifications, will provide a major power source for submersibles.

Despite the opposite extremes of ambient pressures encountered in the thin atmosphere of outer space and the dense ocean medium, in conjunction with other subsequent differences in basic requirements, the lightweight high-strength materials designed for space missions may ultimately be used in marine structures and power plants. Furthermore, the environmental research that has allowed the astronaut to survive in space provides a headstart to efforts to adapt similar survival techniques to underwater conditions.

In general, the experience gained by the aerospace activities in the modern approach to research and development, as well as the detailed management techniques learned, will assist greatly in channeling industrial efforts into the marine fields. In certain instances, the extensive physical plants used to produce aerospace products are being converted to marine system production.

1.2 NAVAL MISSIONS IN THE OCEAN ENVIRONMENT

In an address given at the National Sea-Air-Space Exposition in Washington, D. C., on February 9, 1967, the Chief of Naval Research, RAdm John K. LEYDON, USN, cited the following missions as justification of the Navy's deep sea research program in ocean technology[27]:

> (1) Occupation, for the purpose of exploiting, critical ocean floor sites on the continental shelf off the U. S., sea mounts located near the U. S., continental slopes off the U. S., and similar areas located elsewhere. This would include the use of both dry submersibles (with and without exterior manipulators) and ambient pressure (equalized) fixed or mobile Sealab habitats;
>
> (2) Salvage, recovery and oceanographic rescue operations in ocean waters to 20,000 feet;
>
> (3) Installation, control and operation of weapon systems on the ocean floor in continental shelf areas contiguous to the U. S. and extending depth-wise as a function of time to the abysmal

plain, taking into special consideration sea mounts and ridges. Such systems would be both manned and unmanned locally;

(4) Installation and operation of surveillance systems both on the ocean floor and at mid-depth, taking advantage of the ocean floor topology and sound propagation channels. Such systems would be both manned and unmanned locally;

(5) Provision of the necessary undersea technical support or technology to enable the national expansion and exploitation of the offshore resources by industry in conjunction with other government agencies. Such technology would include but not be limited to life support, vehicles, tools, and communications.

In addition to the foregoing deep sea missions of the Navy, the conventional military underwater weapons systems, such as the ballistic missle-bearing submarine and the torpedo, both ASW and anti-surface ship types, must be constantly re-evaluated and modified as necessary to keep pace with national security needs. Furthermore, intensive efforts must continue in the design and development of modern surface vessels to ensure control of the air-sea interface and thereby guarantee the safe and rapid movement of people and supplies over the surface of the ocean. As indicated by the above objectives, there must be a concert of effort, on the part of the military and industrial interests, to effect the most beneficial exploration and exploitation of the sea.

In order to accomplish the diversity of missions stated above, improvements must be made to present systems and unique systems must be devised. As a means of facilitating the exploration and occupation of the ocean floor, a small specially-designed submarine, the Undersea Research Vehicle (URV), shown schematically in Figure 1, is under development. The URV will offer the advantage of on-the-spot research and control by trained oceanographers to obtain

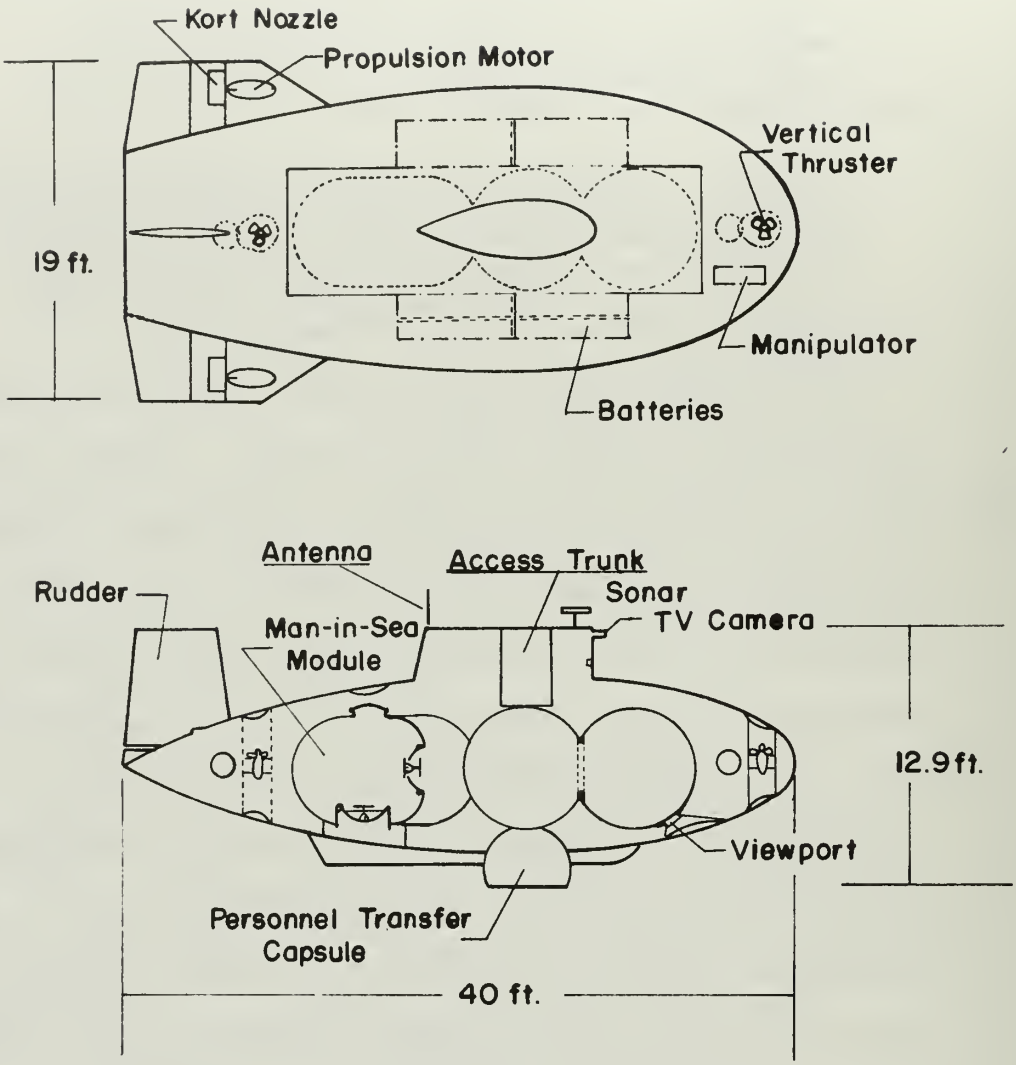


FIGURE 1 DRAWING OF FOUR-MAN VERSION OF PROPOSED UNDERSEA RESEARCH VEHICLE (URV) SHOWING MODULAR CONCEPT AND PERSONNEL TRANSFER CAPSULE (PTC) (REF. 1)

solutions to urgent underwater problems. In order to withstand the high ambient pressures at its operating depths, materials with high compressive strength to density ratios are required for the structural hull design of the URV. Also, to complete its mission, the URV will need a power source with great endurance capabilities.

Occupation and exploitation of the ocean bottom will require the transfer of supplies and personnel to underwater installations in order to replenish and supervise the proper operation of such systems as food-processing plants, oil fields, and similar industries. Personnel Transfer Capsules (PTC), similar to the device shown in Figure 1, will carry teams of divers to sufficient depths along the continental shelf and allow them to leave the vehicles to check and repair surveillance devices. Moored buoys and stable offshore structures can be constructed and monitored by such teams.

The early generation of bathyscaphes, such as Trieste I and Trieste II, as well as the more sophisticated second generation submersibles such as Deep Star, Alvin, and Aluminaut, are being replaced by more efficient systems designed to penetrate deeper into the ocean. Tables I and II present data concerning various properties of bathyscaphes and deep research vehicles. Man-in-the-Sea experiments, with the Sea Lab III tests scheduled for September 1967, are pointing the way to eventual habitation under the sea. Figure 2 depicts the equipment arrangement for Sea Lab II.

New systems, such as the Deep Submergence Rescue Vehicle (DSRV), shown schematically in Figure 3, and the Deep Submergence Search Vehicle (DSSV) are being developed for rescue and recovery missions on the floor of the ocean. When operational in late 1968, the DSRV will be air-transportable and hence capable of rapid arrival at the

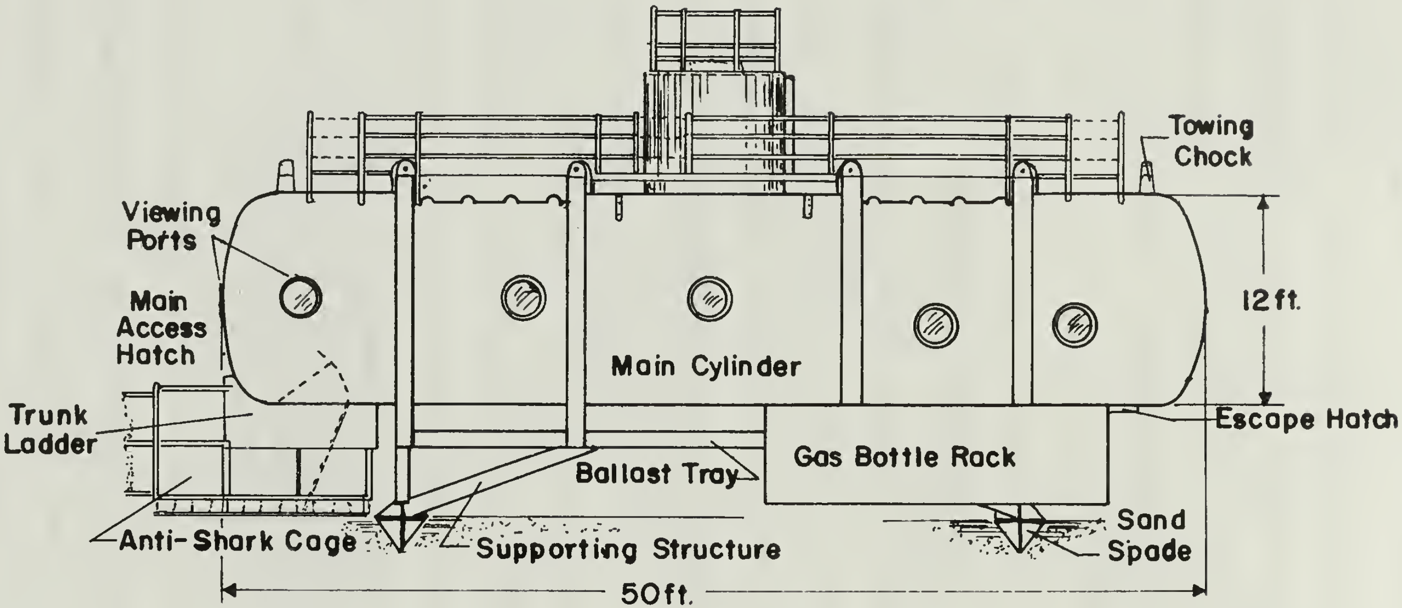


FIGURE 2 SEALAB II EQUIPMENT ARRANGEMENT
(REF. 1)

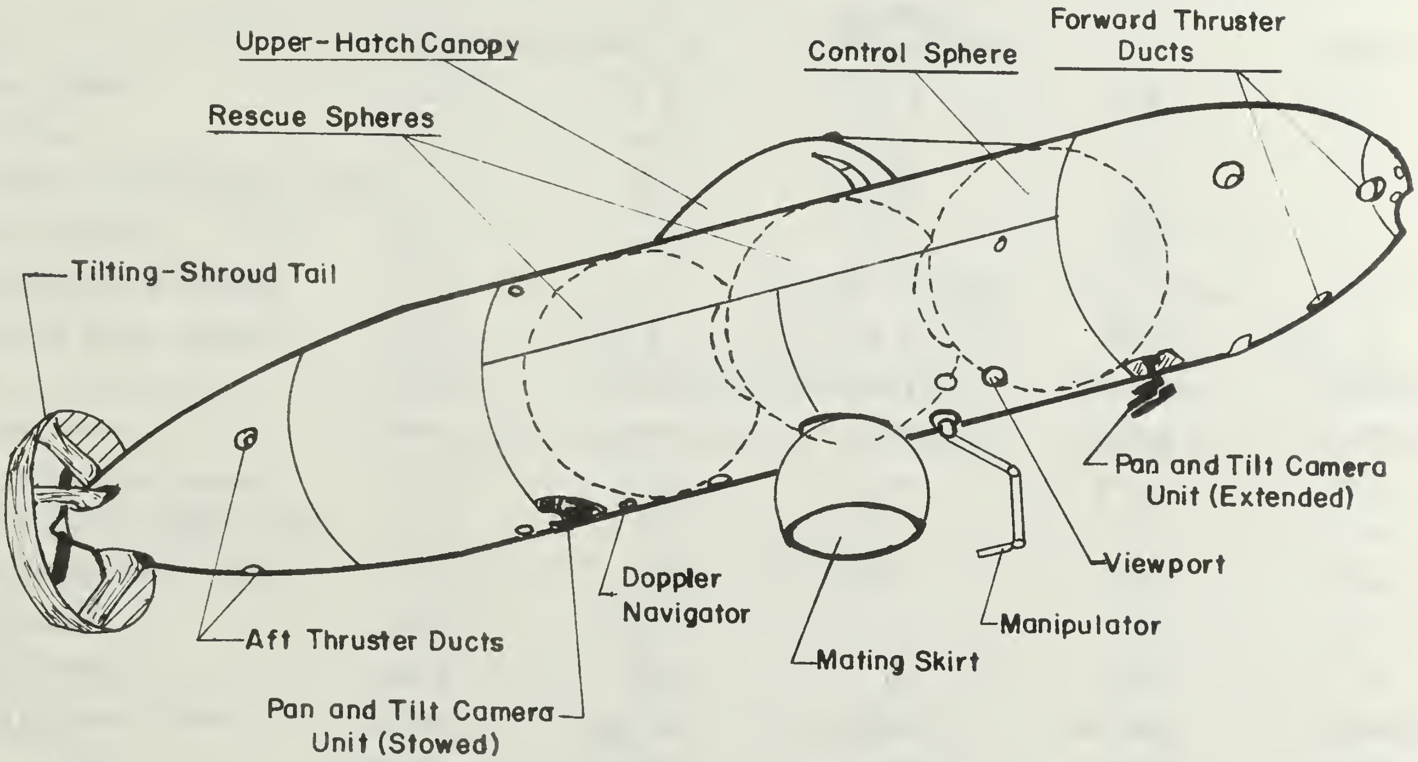


FIGURE 3 DEEP SUBMERGENCE RESCUE VEHICLE (DSRV) EQUIPMENT ARRANGEMENT (REF. 2)

TABLE I. DIMENSIONS AND OPERATING CHARACTERISTICS OF VARIOUS BATHYSCAPHES (REF 1)

Item	Trieste Terki	Trieste Krupp	Trieste II Terki	Trieste II Krupp	Archimede	FRNS III
Operating Deth (feet	20,000	35,300	20,000	35,800	35,800	13,500
Length (feet)	59.5	59.5	67	67	69	53
Beam (feet)	11.5	11.5	15	15	13	16.6
Submerged Displ. (tons)	150	150	220	220	200	100
O.D. of Press. Hull (feet)	7.2	7.2	7.2	7.2	7.87	7.2
P.H. Thickness (inches)	3.54	4.72	3.54	4.72	5.91	3.5
P.H. Material	Forged St.	Forged St.	Forged St.	Forged St.	Forged St.	Cast Steel
Flotation Material	Gasoline	Gasoline	Gasoline	Gasoline	Gasoline	Gasoline
Submerged Speed (Knots)	1	1	2.4	2.4	3	1
Range (Nautical miles)	4	4	14 at 2.4K	14 at 2.4K	7.5 to 15	3 to 5
KW Hours power	60	60	115	115	-	-
Endurance, Life support (hrs)	28	28	28	28	-	-
Complement	2-3	2-3	2-3	2-3	3	2
Payload (tons)	5.0	2.5	3.8	3.8	2	2
Status	Replaced by Trieste II		Built/NEL BUSHIPS	3	Built by French Navy	

TABLE II. DIMENSIONS AND OPERATING CHARACTERISTICS OF VARIOUS DEEP RESEARCH VEHICLES (REF 1)

Item	Alvin	Aluminaut	Trident	Deepstar	Consteau Saucer	Moray TV 1A	Deep Jeep
Operating Depth (feet)	6,000	15,000	18,000	12,000	1,000	2,000	2,000
Length (feet)	20	51.25	46	18	9.5	35	11
Beam (feet)	7.5	10	11	11.5	9.5	5.5	9
Submerged Displ(tons)	15	81	85	9	4	15	3
O.D. of Press. Hull(feet)	6.83		7.0	6.5	Ellipsoid 6.5 x 4.9	5.0	-
P.H. Thickness (inches)	1.33	6.5	2 or 3	1.1875	.75	1.7	-
P.H. Material	Welded steel	Forged Aluminum	Welded steel or titanium	Welded steel	Forged steel	Cast Aluminum	Welded steel
Floation material	Syntactic foam	None	S.F.	None	None	S.F.	S.F.
Submerged Speed (XTS)	4.6	3.8	4-5	3	1	15	2
Range (Nautical miles)	25 to 2.5	80 at 3	80 at 3	20	4	40 at 3	8 at 2
KW Hours Power	50	160	270	-	-	50	-
Endurance, Life support (hrs)	24	72	24	48	24	36	52
Complement	2	3-5	3	2-3	2	2	2
Payload (pounds)	1,200	3,400	3,000	-	100	-	-
Status (Jan. 1965)	Built	Built	Prel. Design Comp.	Under Const.	Built Operated	Built being tested	Built being tested

scene of a disaster. It will ride "piggy back" on a "mother" nuclear-powered submarine and will be capable of performing its rescue mission down to the 3500 foot level. The DSSV is being planned for operations at the ocean bottom at a maximum depth of 20,000 feet and will be capable of searching for and recovering small objects from the floor of the sea. Vehicles and machinery necessary for the salvage of large objects are presently under construction and will incorporate a Personnel Transfer Capsule (PTC) containing teams of divers required for the operation of the system. Diving personnel will be provided with individual swimming equipment, including Swimmer Delivery Vehicles (SDV), several of which are operational or soon to be delivered to the fleet.

To provide the technical support and logistics flow required for the exploitation of offshore resources, large cargo-carrying submarines, or tractor subs capable of towing containers similar to tank cars will be needed. For close manual work, such as cleaning or repairing positioned equipment, manipulators similar to the unmanned Cable-Controlled Underwater Research Vehicle (CURV) or the recently completed device called AUTEC are available. This latter vehicle contains the operator controls, manipulators, a wide variety of tool attachments, and viewing aids in one completely coordinated machine. The possibility of untethered, telemetry-controlled devices of this nature is being thoroughly investigated.

Polaris submarines and the new torpedo and missile weapons systems being developed will continue to pose both a strategic and tactical problem to our enemies. Modification and improvement of present systems will result in an increase in performance at greater depths. More advanced propulsion systems will be required to allow for operation at these depths.

The torpedo, which is the primary underwater weapon against surface ships, is also being developed as an antisubmarine weapon system and is presently undergoing extensive testing at the Naval Underwater Ordnance Station at Newport, R. I., and the Naval Ordnance Test Station, China Lake, California.

New propulsive systems and recommended changes in the standard configuration and dimensions of torpedoes could result in major modifications to this weapon in the near future. One system which is very intriguing and under current investigation, is the so-called "power down the line wire system." Figure 4 shows the general features of this system which uses electrical energy supplied through a cable to run an electric propulsion device. Several applications of this concept are being investigated for oceanographic research purpose and will entail the manipulation of an unmanned vehicle from a "mother" ship on the surface.

For operations along the air-sea interface, surface support ships are being constructed for oceanographic missions and for use in conjunction with search and rescue deep diving submersibles. Special equipment and well-trained personnel aboard the "mother" ships, such as the Auxiliary Submersible Rescue (ASR) or the SSN, which is the submergible nuclear vessel used with the DSRV, will greatly assist in the performance of assigned missions. Other surface ships will be used in mining operations along the continental shelf and in the placement of structures and buoys for navigation and surveillance purposes.

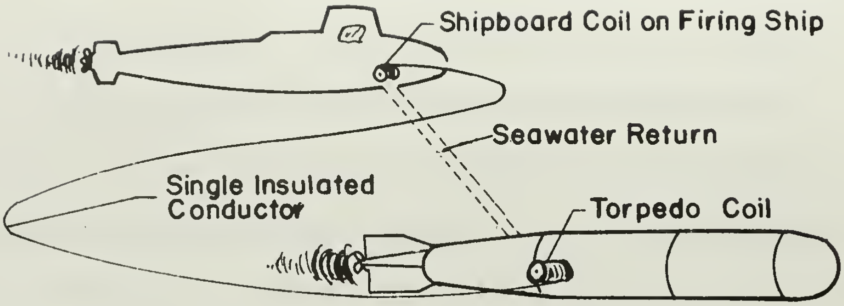


FIGURE 4 TORPEDO WEAPONS SYSTEM DRIVEN BY "POWER DOWN THE LINE" SYSTEM (REF. 29)

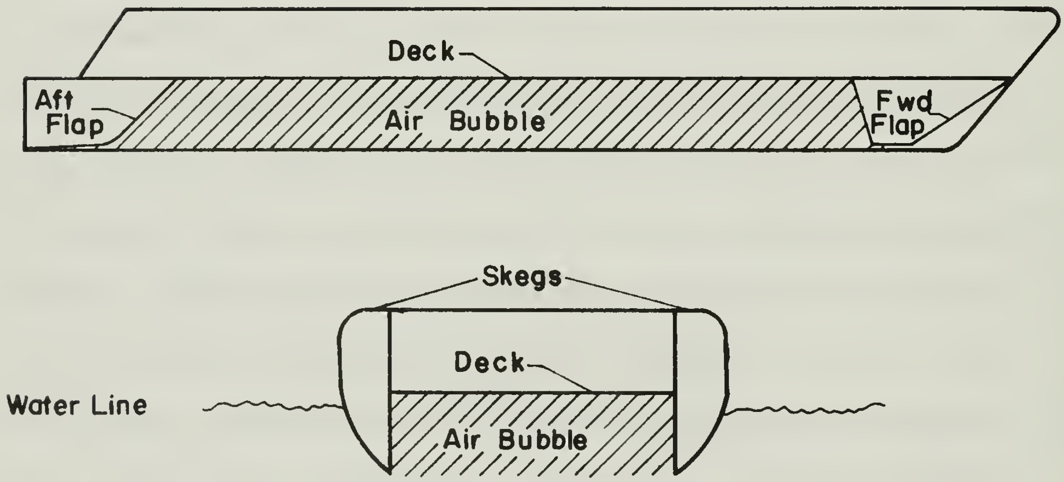


FIGURE 5 SCHEMATIC DRAWING OF CAPTURED AIR BUBBLE (CAB) CRAFT (REF. 129)

For higher speeds and faster supply and personnel delivery missions, various types of Surface Effect Ships (SES) and hydrofoil craft are under development. The Surface Effect Ships, known alternatively as Ground Effect Machines (GEM), can be separated into two categories: Air-Cushion Vehicles (ACV) and Captured Air Bubble (CAB) devices. These vehicles are capable of speeds in the neighborhood of eighty knots, but suffer from control difficulties at these speeds or in high sea states. Hydrofoil vehicles, on the other hand, are being tested for use as amphibious landing vehicles and, despite speed limitations due to cavitation problems in the propulsion system, could be extremely valuable if such difficulties are worked out satisfactorily. See Figures 5 and 6.

1.3 PURPOSE OF THE PRESENT STUDY

The above discussion only touches lightly upon the numerous highly advanced vehicles required to accomplish the diversified, complex missions assigned the military in general, and the Navy, in particular. It is obvious that one important aspect of the proposed work lies in the design, development and testing of the underwater propulsion systems that will be needed to power the various vehicles and weapons systems utilized in the performance of these missions. Many of these propulsion units involve techniques and principles that have seen wide usage in air and surface applications, and their conversion to hydronautic power systems has been straightforward. Indeed, several of the aerospace propulsion concepts were originally designed for employment in undersea devices. However, there are several propulsors which are unique for obtaining thrust in the water environment, and such devices are discussed in this paper.

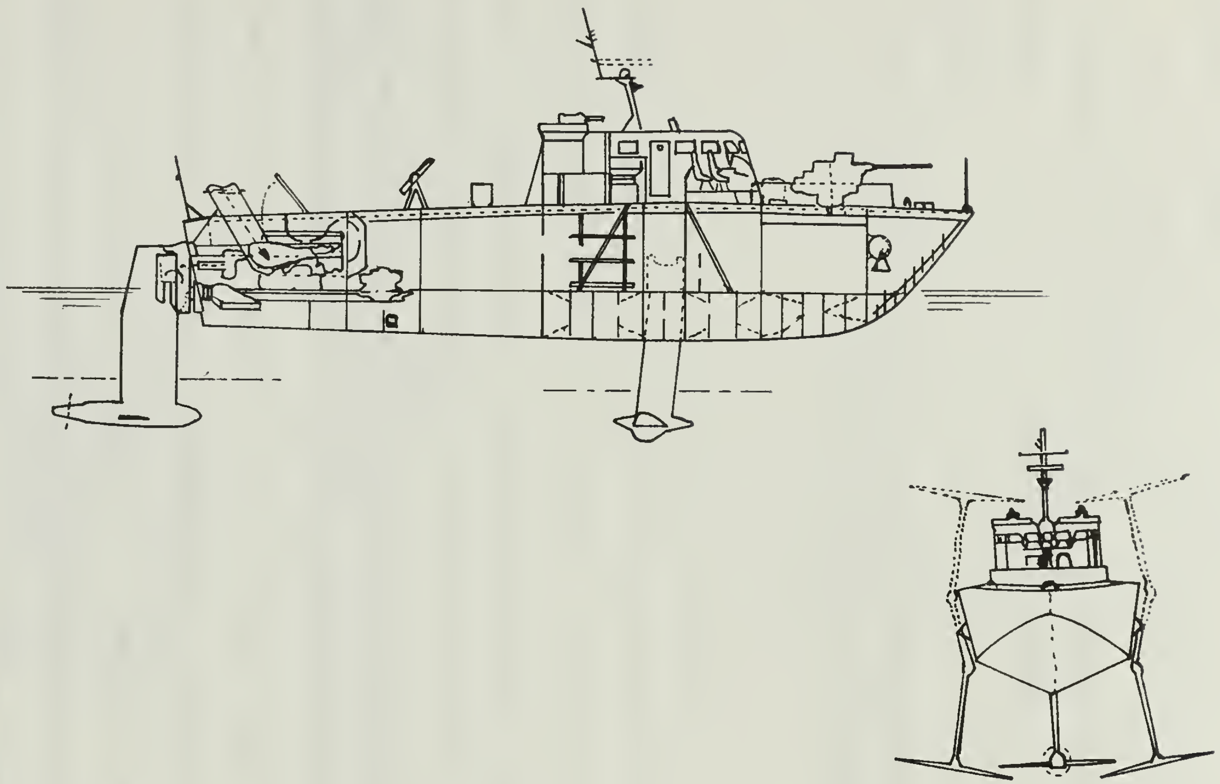


FIGURE 6 HYDROFOIL CRAFT (CONFIGURATION OF PGH-1) (REF. 128)

While not dwelling to any great extent on the basic thermodynamic power cycles or the overall propulsive power sources themselves, a definite distinction is established among the energy source, power cycle, and thrust-generating device. A general classification of the propulsors is decided upon, and performance parameters are discussed. The various thrust devices themselves are described and analyzed in detail. Due to the wide divergence of missions and the large number of performance parameters that could be considered, a critical comparison of the overall performance of marine propulsors on an absolute basis would be most difficult. However, an attempt to compare these devices on an efficiency basis will be made. This will be accomplished by first, carefully defining exactly what is meant by the efficiency parameter, and then converting the unit terminologies to a common one in an effort to arrive at a suitable comparison. Where feasible, a comparison of thrust and thrust augmentation capabilities will also be made after appropriate definitions are stated. Primary emphasis will be placed on those systems which appear to be unique and hold promise for rapid and important advances in the marine propulsor field. An attempt is also made to determine which thrust device is most appropriate for mating with the various vehicles and marine systems used or under development for the underwater missions confronting the Naval establishment. It must be realized that such a determination can serve only as a general guide and that overall performance characteristics and particular mission requirements must be examined for a realistic appraisal. This paper is intended as a compendium on marine propulsors and consequently a sizeable bibliography is included.

CHAPTER 2

OVERALL PERFORMANCE CONSIDERATIONS

Prior to presenting the theoretical analyses for the individual marine thrust generators, it is deemed appropriate to discuss the propulsion process in general with due emphasis on the classification of thrust devices and also define and derive those performance parameters which will later constitute the basis for a systems comparison. As stated in Chapter I, a primary objective of the present study is the recognition and formulation of common performance parameters existing among the various propulsive devices. This would enable one to select that unit which, on a comparative basis, is most desirable for use with a particular marine vehicle or weapons system.

2.1 CLASSIFICATION OF THRUST DEVICES

As a first step towards accomplishing this purpose, a meaningful scheme of categorizing the propulsors is needed. One consideration in this regard, seemingly elementary but sometimes ignored in the literature,is the necessity of distinguishing between the energy producer and the energy converter in a certain propulsion system. Inasmuch as our principal concern is with the performance of the individual thrust generators, rather than the power sources, an attempt has been made to completely divorce the thrust device from the basic energy-producing system. In analysing each propulsor, it was assumed that the operation of the thrusting device was independent of the energy source and, therefore, a general level of performance criteria could be obtained.

Careful consideration of the general thrust generating process indicates that there must be a transfer of energy from one fluid medium to another. There are two distinct methods of accomplishing such an energy transfer: (1) the direct method, exemplified by the ejector or jet device and (2) the indirect transfer of energy by rotating or reciprocating machinery. Since these two methods would appear to provide a quick dichotomy of the numerous propulsors, they have been established as the most general categories in this study and the devices have been classified as either propeller-type or jet propulsors.

Having decided on the above classification of propulsive devices, it was difficult to determine the exclusive category to which each marine propulsor belongs. Commencing with the conventional water screw, and progressing through the improved modern rotating devices that have developed, a difficulty in categorization arose with the analysis of the so-called psuedo-blade propulsor. This unique device operates in a manner which combines the direct and the indirect methods of energy transfer and hence, following our classification procedure, could be placed in either category. However, for reasons stated in the section devoted to this special device, it is considered to belong to the rotating class of propulsors.

The ultimate assignment of categories of marine propulsors follows closely the method used in classifying air thrusting devices. The hydrodynamic counterparts of the ramjet, pulsejet, and rocket are clearly jet-type units since they have no rotating parts. However, the turbojet and pumpjet, or waterjet, which relies on impeller action, but exhausts directly into the surrounding medium,present a classification problem. Also, the shrouded or ducted propeller appears to fit both class descriptions. Upon consideration of the two methods of thrust production, it was decided that the turbojet, pumpjet and ducted propeller fit more readily into the jet propulsor category due to the presence of a nozzle in the system and the ability to vary the nozzle exit area, thus directly effecting the exhaust flow.

It may appear that too much emphasis has been given to the problem of classifying the various propulsion units, but throughout the preparatory research stages of this study, no absolute categorization and identification of marine thrustors was found in the literature. Furthermore, it was anticipated that a worthwhile comparative analysis of performance between two devices operating on significantly different principles might be a tenuous matter, whereas an inter-group comparison would be obtainable and beneficial. The scarcity of investigations and test results in the relatively new field of hydrodynamic jet propulsors naturally results in a constraint on the number and accuracy of performance parameters for this category and indicates the likelihood of a restriction to evaluation of performance among members of the same grouping.

2.2 GENERAL ANALYSIS OF PROPULSION SYSTEMS

Every propulsion system, marine as well as air, is constructed with one purpose in mind, the creation of thrust. The various methods employed to propel a body through any fluid medium are based on Newton's second and third laws of motion. The second law states that a force is required to increase the momentum of a fluid. The third law requires every force to have an equal and opposite reaction. Thus, if the working fluid has its momentum increased as it passes through the vehicle, the reactive force (exerted by the fluid on the vehicle) will be a positive thrust. The airplane propeller, ship screw and jet propulsion device all perform similar functions by increasing the momentum of the working fluid, but they differ primarily in the magnitude of the mass flow rate and velocity change of the medium involved in their particular operation. A propeller, in general, takes a large volume of fluid and moves it to the rear at a comparatively low speed. The jet device, on the other hand, takes in a relatively small mass of working fluid, but accelerates it rearward into the surrounding medium at a very high velocity. Of course, the larger the mass of the fluid and/or the greater the acceleration imparted to it, the more thrust the device generates.

In order to demonstrate the principles involved in the generation of thrust by an arbitrary propulsion system, consider the control volume enclosing the system shown in Figure 7. It is assumed that the flow is steady; i.e., there is no time variance in any properties of the flow, that the end planes A are of infinite length and perpendicular to the direction of fluid flow, and that the flow is uniform far from the body. The coordinate system is fixed to the propulsion device with the flow from left to right, having the properties as shown in the diagram. A general propulsive thrust equation will be derived by making a momentum flux analysis across this control volume in the x-direction.

For steady flow, the continuity equation becomes:

(mass flow rate into control volume) =

(mass flow rate out of control volume)

or

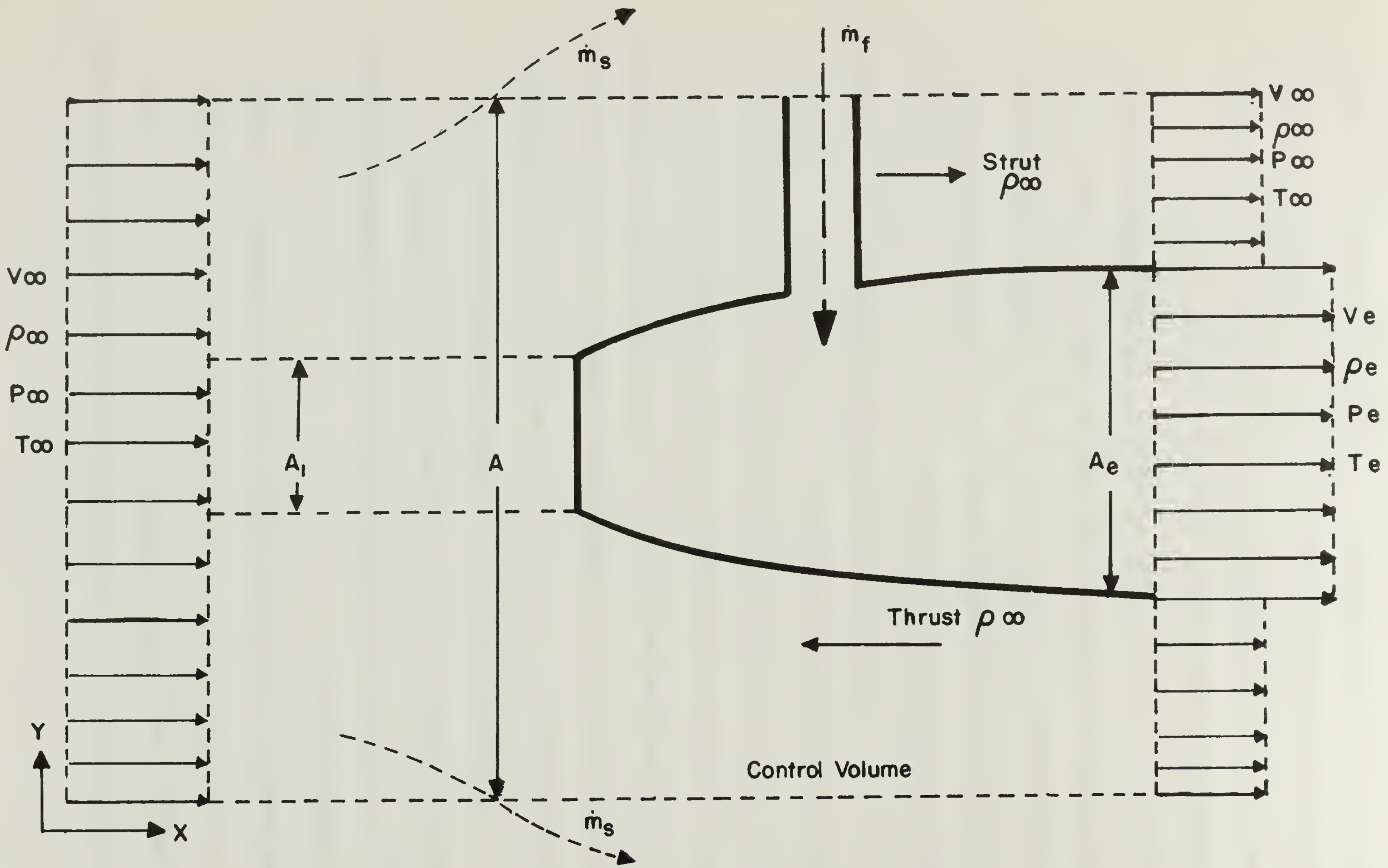


FIGURE 7 ARBITRARY PROPULSION SYSTEM ENCLOSED IN CONTROL VOLUME

$$\rho_\infty V_\infty A + \dot{m}_f = \dot{m}_s + \rho_\infty V_\infty (A - A_e) + \rho_e V_e A_e. \qquad (1)$$

The fuel mass flow, $\dot{m}_f$, is expressible as

$$\dot{m}_f = \rho_e V_e A_e - \rho_\infty V_\infty A_1 ,$$

and when this value is substituted into eq. (1), we can solve for the mass flow, $\dot{m}_s$, which is lost through the sides of the control volume:

$$\dot{m}_s = \rho_\infty V_\infty (A_e - A_1). \qquad (2)$$

For steady flow, the net momentum flux out of a control volume is equal to the resultant of the external forces acting on the control volume:

$$\sum F_x = \int_{c.s.} V_x \rho (\vec{V} \cdot \hat{n}) \, d\sigma ,$$

where $\hat{n}$ is defined as the unit outward vector perpendicular to the control surface and the integration is over the surface of the control volume.

The external forces acting on the system can be independently evaluated:

$$\sum F_x = p_\infty A + T - p_\infty (A - A_e) - p_e A_e$$

$$= T + A_e (p_\infty - p_e), \qquad (3)$$

where T is the thrust.

Evaluating the momentum flux term:

$$\int_{c.s.} V_x \rho(\vec{V}\cdot\hat{n})d\sigma = \text{momentum flux out}\Big]_x - \text{momentum flux in}\Big]_x$$

$$= \dot{m}_s V_\infty + \rho_\infty V_\infty^2 (A - A_e) + \rho_e V_e^2 A_e - \rho_\infty V_\infty^2 A.$$

Note that the propellant mass flow, $\dot{m}_f$, has no initial x-component. Substituting the value found for $\dot{m}_s$ from eq. (2) yields

$$\int_{c.s.} V_x \rho(\vec{V}\cdot\hat{n})d\sigma = \rho_\infty V_\infty^2 (A_e - A_1) - \rho_\infty V_\infty^2 A_e + \rho_e V_e^2 A_e$$

$$= \rho_e V_e^2 A_e - \rho_\infty V_\infty^2 A_1 .$$

Let $\dot{m}_e = \rho_e V_e A_e$ = mass flow out the exit,

and $\dot{m}_i = \rho_\infty V_\infty A_1$ = mass flow through the inlet.

Then,

$$\Sigma F_x = \dot{m}_e V_e - \dot{m}_i V_\infty . \qquad (4)$$

From eqs. (3) and (4):

$$T + A_e(p_\infty - p_e) = \dot{m}_e V_e - \dot{m}_i V_\infty ,$$

or finally,

$$T = \dot{m}_e V_e - \dot{m}_i V_\infty + A_e(p_e - p_\infty). \qquad (5)$$

This is the basic thrust equation where the first two terms combined represent the change in momentum flux through the propulsion system, and the last expression is the net pressure force over the exit plane. Equation (5) actually gives the action force which accelerates the fluid from V_∞ to V_e, and the thrust is the reaction to that force or the force component in the x-direction exerted by the fluid on the interior surfaces of the propulsion system.

In eq. (5) above, the expression $\dot{m}_e V_e$ is called the jet thrust, the term $\dot{m}_i V_\infty$ is known as the inlet or ram drag, and $A_e(p_e - p_\infty)$ is the pressure thrust. By introducing the so-called effective jet velocity, V_j, eq. (5) can be rewritten as:

$$T = \dot{m}_e V_j - \dot{m}_i V_\infty , \qquad (6)$$

where $V_j = V_e + (p_e - p_\infty)/\rho_e V_e .$

Obviously, where the exit pressure and ambient pressures are equal, the pressure thrust is zero, $V_j = V_e$ and the thrust force is just equal to the change in momentum flux. In general, in the analyses to follow, the two end planes are considered to be far enough away from the propelled body to allow the wake pressure to stabilize and assume the value of the ambient pressure of the medium. For the case of the conventional jet propulsion device, eq. (5) or eq. (6) may be used for thrust calculations. If it is assumed that $\dot{m}_f << \dot{m}_i$, then

$$\dot{m}_e = \dot{m}_i + \dot{m}_f \cong \dot{m}_i$$

and thrust can be written:

$$T_{jet} = \dot{m}_e (V_e - V_\infty) + A_e (p_e - p_\infty) \qquad (7)$$
$$= \dot{m}_e (V_j - V_\infty) \cong \dot{m}_i (V_j - V_\infty).$$

In the case of the rocket engine, the inlet area $A_1 = 0$, and, therefore, the ram drag is equal to zero. The thrust for a rocket is given by:

$$T_{rocket} = \dot{m}_e V_e + A_e (p_e - p_\infty) \qquad (8)$$
$$= \dot{m}_e V_j .$$

Another important parameter in determining the performance of a rocket is the specific impulse:

$$I_{SP} \equiv \frac{\text{thrust}}{\text{mass flow of propellant}} \equiv \frac{T}{\dot{m}_f} .$$

For a propeller-type propulsion system, $\dot{m}_f = 0$ and we assume $p_e = p_\infty$; thus, the basic thrust equation reduces to

$$T_{prop} = \dot{m}_e (V_e - V_\infty). \qquad (9)$$

But, $V_j = V_e$, and the equation can be rewritten as

$$T_{prop} = \dot{m}_e (V_j - V_\infty), \qquad (10)$$

which is the same thrust relationship as for a jet propulsion system.

The thrust equations, derived thus far, involve net thrust as opposed to total, gross, available or other such terminology. The above thrust equations include ram drag losses, but do not consider such thrust reduction factors as hull-propulsor interference losses, which would result in an available thrust term. When discussing thrust or torque in the following theoretical analyses, net thrust is intended unless specifically stated otherwise.

2.3 PERFORMANCE PARAMETERS

The preceding general analysis for an arbitrary thrust generator and the resultant thrust expressions as applied to marine jet propulsors and propeller elements will serve as the basis for the assignment of various performance parameters for use in evaluating the propulsion units. Since many authors use the terms thrust, efficiency, power, etc., in a general sense and with a variety of concepts in mind, it would seem imperative to establish definitions for these terms as early as possible and adhere to strict terminology in order to avoid a possible avenue of confusion.

The properties selected for evaluating the performance of the propulsors include: thrust, torque, efficiency, and thrust augmentation ratios, where appropriate. These parameters can be expressed as dimensionless coefficients by showing that the thrust is proportional to the product of the dynamic pressure, $q = \frac{1}{2}\rho V^2$, and a representative area $S \propto D^2$, where D is the diameter of the propeller or of the exhaust area in a jet or rocket device:

$$T \propto qS \propto \rho V^2 D^2 .$$

But, $V \propto nD$, where n is revolutions per unit time and so,

$$T \propto \rho n^2 D^4 ,$$

or $T = C_T(\rho n^2 D^4)$, where the coefficient of proportionality

$$C_T \equiv \frac{T}{\rho n^2 D^4} . \tag{11}$$

Introducing the effective speed ratio,

$$\nu = \frac{V_\infty}{V_e} , \tag{12}$$

the expression for the coefficient of thrust for the propeller is arrived at as follows:

$$C_{T_{prop}} = \frac{\dot{m}_e V_\infty \left(\frac{1}{\nu} - 1\right) + A_e (p_e - p_\infty)}{\rho n^2 D^4} . \tag{13}$$

In the case of the rotating thrust devices, the coefficient of torque becomes an important parameter in determining individual performance. The torque Q is defined as the rotating force times its radius of application and, therefore, is given in units of work; e.g., ft-lb_f. In most instances in the literature and throughout this study, the coefficient of torque will be defined in a manner similar to the coefficient of thrust:

$$C_Q \equiv \frac{Q}{\rho n^2 D^5} . \tag{14}$$

Many efficiency parameters are used for a number of separate purposes in the literature. It is felt that no useful purpose would be served by discussing all the different efficiencies to be encountered, and, therefore, only the following expressions after Zucrow[60] are used in this study:

The <u>propulsion power</u>, which is the rate at which kinetic energy is supplied by the propulsor to the working fluid, is denoted by $\mathbb{P}$. Recalling that

$$K.E. = \frac{1}{2} m V^2 ,$$

we can express the propulsion power as

$$\mathbb{P} = \frac{d}{dt}\left(\frac{1}{2} m V^2\right)$$
$$= \frac{\dot{m}}{2}\left(V_e^{\,2} - V_\infty^{\,2}\right).$$

The <u>thrust power</u>, $\mathbb{P}_T$, which is the rate at which useful work is performed by the propulsion system, is given by

$$\mathbb{P}_T = T V_\infty ,$$

where the expression for thrust depends on the type device involved.

Since all thrust devices create a certain amount of energy which is shed in the wake, not all of the propulsion power is converted into thrust power. This inherent loss is termed the <u>exit loss</u> and is denoted by $\mathbb{P}_L$:

$$\mathbb{P}_L = \frac{\dot{m}}{2} u^2 ,$$

where u is the relative exit velocity, that is,

$$u = V_j - V_\infty , \quad \text{for a jet device}$$

and

$$u = V_e - V_\infty , \quad \text{for a propeller.}$$

In addition to the inescapable exit loss, there are other losses to be considered in a real system; such as, internal friction losses, losses due to the divergence of the exhaust jet, and swirl losses. However, assuming an ideal propulsor, these additional losses can be disregarded, and the power term is

$$\mathbb{P} = \mathbb{P}_T + \mathbb{P}_L$$
$$= T V_\infty + \frac{\dot{m}}{2} u^2 .$$

In terms of the effective speed ratio, ν,

$$\mathbb{P} = \frac{\dot{m}}{2} V_e^2 (1 - \nu^2).$$

The <u>ideal propulsive</u> efficiency is given by

$$\eta_p = \frac{\mathbb{P}_T}{\mathbb{P}_T + \mathbb{P}_L} . \qquad (15)$$

Expressing the ideal propulsive efficiency in terms of the effective speed ratio, ν, we get

$$\eta_p = \frac{2\nu}{1 + \nu} \quad \text{(for jet and propeller devices)} \qquad (16)$$

and

$$\eta_p = \frac{2\nu}{1 + \nu^2} \quad \text{(for rocket propulsor).} \qquad (17)$$

Equations (16) and (17) are plotted in Figure 8 and examination of these graphs shows that as the speed ratio ν approaches unity; i.e., $V_\infty = V_e$, then the ideal propulsive efficiency approaches 100 per cent. It should be pointed out, however, that if the entrance and exit velocities do not differ, the momentum thrust disappears. Furthermore, as the velocity difference increases, ν gets smaller, and the ideal propulsive efficiency is seen to drop off. In a jet device, this velocity differential is considerable, and, hence, the efficiency, η_p, is usually much lower than for a propeller unit. As for the propulsive efficiency of a rocket, the speed ratio is more critical, and a large velocity increase at the exit over the speed of the propulsor results in a rapid decrease in η_p.

It may be more advantageous to describe the performance of a system by its <u>overall efficiency</u>, η_o, which is the ratio of thrust power to the rate at which energy is supplied to the system.

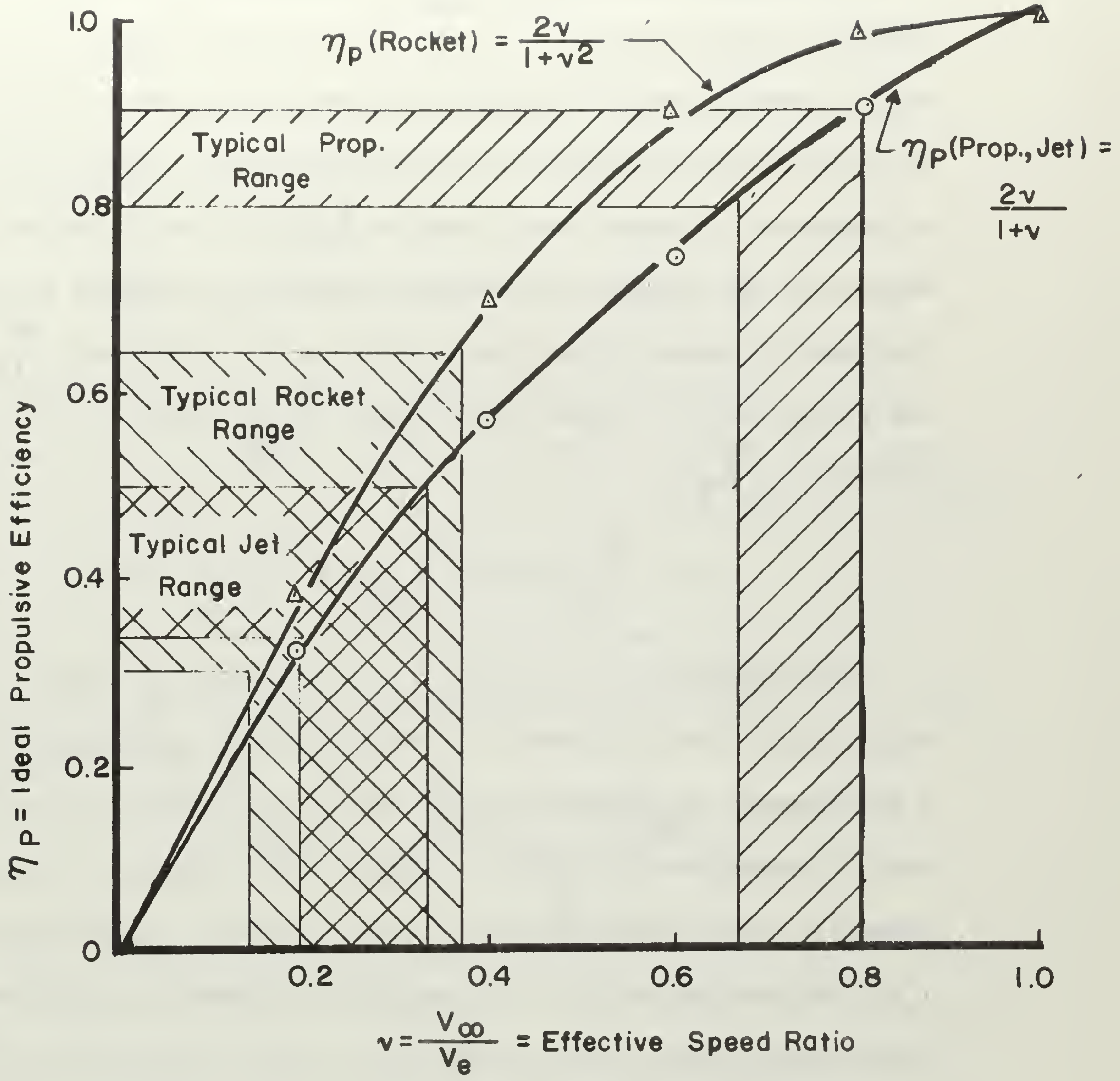


FIGURE8 COMPARISON OF IDEAL PROPULSIVE EFFICIENCIES FOR PROP, JET, ROCKET

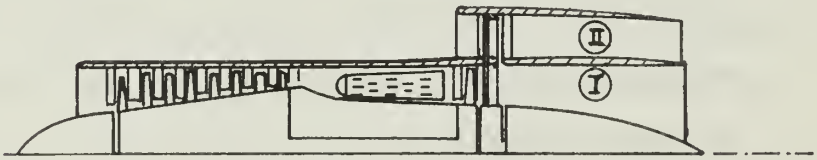


FIGURE 9 SKETCH OF TURBOFAN INDICATING PRIMARY I AND SECONDARY II FLOWS (REF. 11)

The thermal efficiency, η_{th}, is defined as the ratio of propulsion power developed to the rate at which energy is supplied to the system. For a propeller-type device, the thermal efficiency is the efficiency with which the thermochemical energy of the fuel is converted to shaft power, whereas η_{th} for a jet propulsor is a measure of the efficiency with which the fuel is burned to increase the kinetic energy of the fluid. The overall efficiency, η_o, is the product of the thermal efficiency, η_{th}, and the ideal propulsive efficiency, η_P:

$$\eta_o = \eta_{th} \times \eta_P \; . \tag{18}$$

Since marine vehicles travel at relatively low speeds, the efficiency of any jet device is very low, and, consequently, there is a requirement for augmentation of the thrust generating process. This may be accomplished by several methods: addition of a duct to a propeller, the condensuctor or ejector concept, water augmentation in a gas turbine engine, etc. In seeking performance parameters for comparison purposes, the possibility of thrust augmentation ratios was considered where applicable. Augmentation ratios, defined for each device, are treated as important performance indicators, and an attempt is made to compare these ratios when possible.

A thrust augmentation ratio may be defined, in general, as the ratio of the total thrust acting on a system with augmentation to the thrust without augmentation; e.g., for the turbojet case, ratio of thrust with afterburner in operation to thrust without afterburner. In order to obtain a maximum thrust augmentation ratio, it is necessary to obtain the highest possible total outlet momentum by ensuring a large mass flow and/or a high velocity through the exit plane.

In dual flow systems; e.g., the turbofan as shown in Figure 9, the definition of an augmentation ratio is more complex. Foa[11] presents a thorough discussion of the type of system and defines a thrust augmentation ratio as:

$$\alpha_r = \text{Augmentation Ratio} = \frac{T_a}{T},$$

where T is the thrust of the primary system alone and T_a is the "augmented" thrust of the double-flow system. The primary system is the energy-transferring flow, subscripted I, whereas the secondary flow, subscripted II, is the energy-receiving system. Using the subscript I$'$ to reflect the case when the primary system is not transferring any energy to the secondary, we can express the thrust augmentation ratio as follows:

$$\alpha_r = \frac{T_I + T_{II}}{T_{I'}}.$$

Many research facilities have contributed to the study of thrust augmentation as applied to aerospace rockets, and the result has been a significant increase in the performance of air-breathing rockets. Increases in specific impulse of solid propellant rocket motors on the order of 50 to 100 per cent have been reported. Perini, et al.,[187] analysed a 45 per cent aluminum propellant which is capable of a normal specific impulse of about 250 seconds and reasoned that with air augmentation the specific impulse could be increased by 100 seconds. Even greater gains are anticipated when mixing problems are satisfactorily solved and combustion and nozzle efficiencies are increased to optimum values for overall propulsor design.

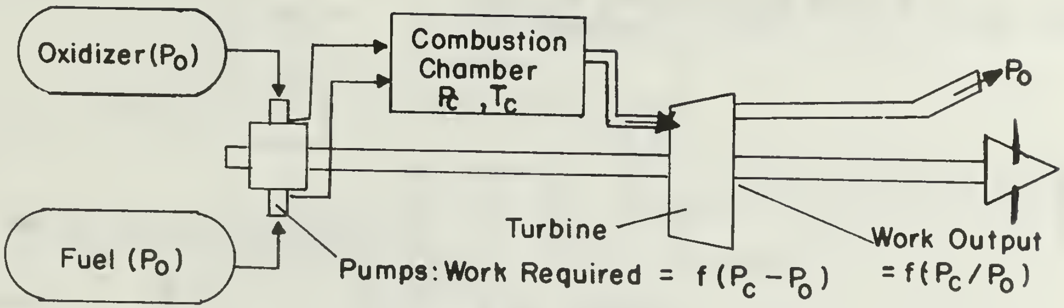
2.4 THERMODYNAMIC POWER CYCLES

A discussion of power plant versus propulsor leads to a consideration of the thermodynamic cycles that are operable with marine propulsion systems. In those systems where the power plant will be operating below the surface continuously and probably at great depths, the fact that it is isolated from the oxygen-bearing atmosphere and the high pressures associated with submergence must be considered.

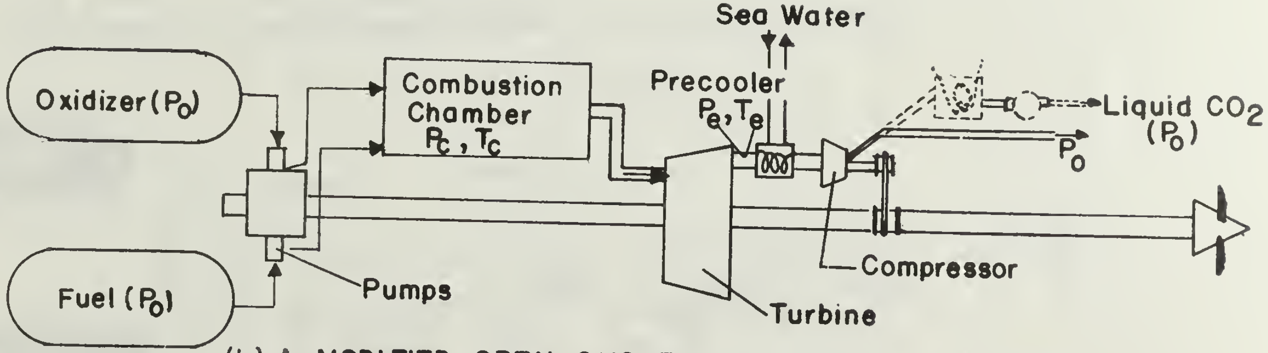
There are three fundamental thermodynamic cycles: (1) basic open-cycle, (2) the modified open-cycle, and (3) the closed-cycle. See Figure 10. Depending on the design environment of the given power plant, the choice of cycle is relatively simple; however, various combinations and modifications have resulted in a number of workable thermodynamic cycles that can either operate immune to depth pressure by using a closed loop or exhaust directly into the surroundings with an open-cycle scheme. Some of the more sophisticated cycles are classified, and thus the three basic types will only be discussed in general terms.

In describing the thermodynamic power cycles, the chemical-fueled power plant will be employed as a primary basis for the discussion in a manner similar to that of Green[19]; however, with regard to systems using nuclear or electrical power sources, the processes are quite similar as will be evident in the following section referring to the various power supply systems.

The typical open-cycle system consists of a fuel and oxidizer tank arrangement, or a similar setup containing the propellants or energy supply, which are subjected to the ambient depth pressure, p_a.

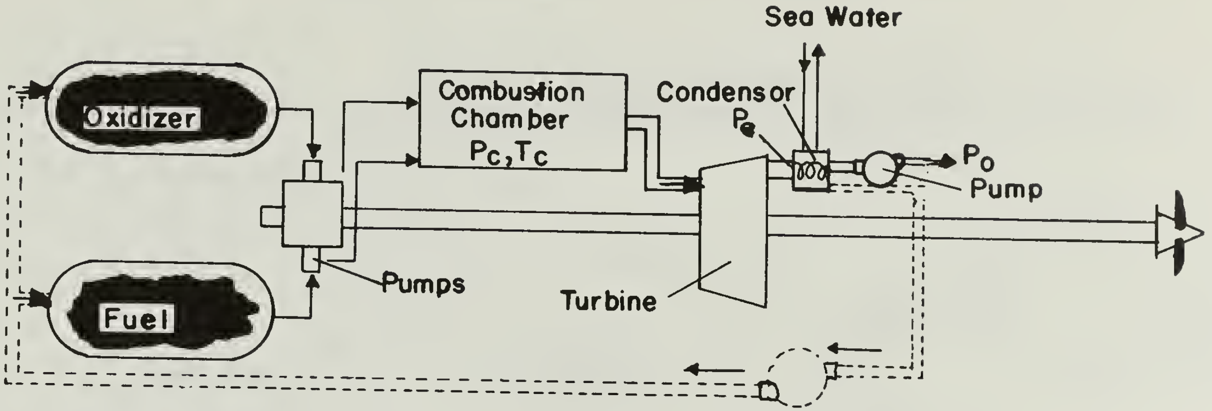


(a) THE BASIC OPEN CYCLE: DIRECT EXPANSION AGAINST DEPTH PRESSURE (REF. 19)

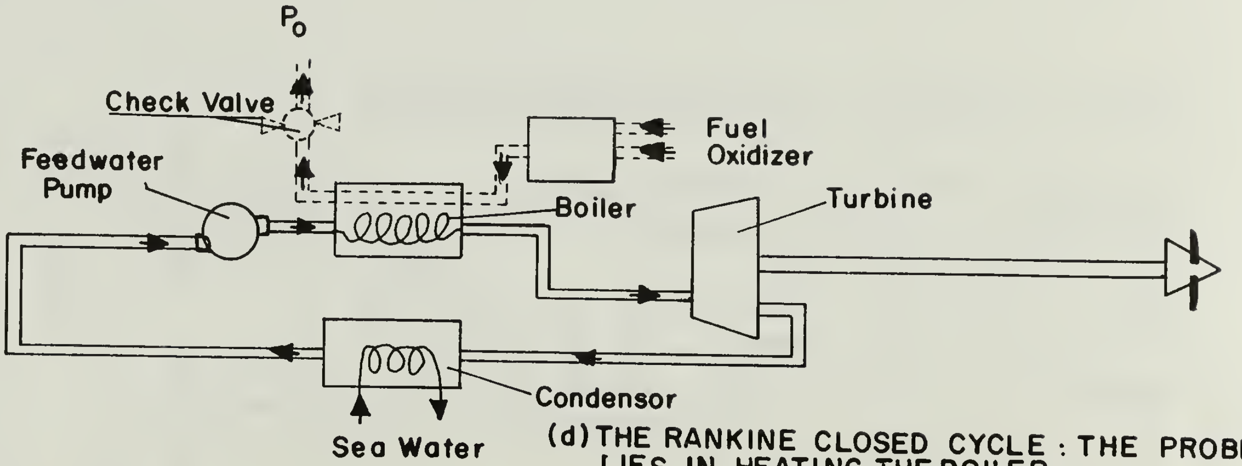


(b) A MODIFIED OPEN CYCLE: INCREASED EXPANSION FOLLOWED BY EXHAUST PUMPING (REF. 19)

FIGURE 10 (a and b) THERMODYNAMIC POWER CYCLES (REF. 19)



(c.) AN EXHAUST-CONDENSING SYSTEM: A TRANSITION FROM THE OPEN TO THE CLOSED CYCLE (



(d) THE RANKINE CLOSED CYCLE : THE PROBLEM LIES IN HEATING THE BOILER

FIGURE 10 (c and d) THERMODYNAMIC POWER CYCLES (REF. 19)

For the chemically fueled power plant, a pumping apparatus transfers the fuel to a combustion chamber where hot gases are generated at chamber conditions, p_c and T_c. The gases are then expanded through a turbine that either provides the rotative power for turning both the propellers and pumps, in the instance where the propeller-type thrust device is used, or provides the power to operate the pumps, and then the turbine exhaust gases are vented directly into the surrounding fluid for jet-type thrust.

A modification to the basic open-cycle system consists in operating the turbine at some exhaust pressure, p_{exh}, that would be less than ambient and then employing an intercooler and compressor to return the exhaust gases to depth pressure. The increased expansion capability allows for a greater amount of work but at a sacrifice in simplicity. Further refinements to the open-cycle involve condensing the exhaust gases, thus requiring less work in the expulsion process and obtaining a decided power advantage.

The closed-cycle system offers the advantage of utilizing a hermetically-sealed capsule that can operate at any depth with unaffected performance. The simplest closed-cycle scheme is the Rankine loop which has a boiler, turbine, condenser, and feed water pump as shown in Figure 10d. This is a system similar to that used in nuclear submarines and steam-powered surface ships, the only variation being the method used to heat the boiler.

2.5 ENERGY SOURCES

There are three general categories of marine-power sources: electrical, thermochemical, and mechanical. Those sources which produce electrical energy and, therefore, drive electric motors to be used with rotating propulsors, are:

(1) Chemical batteries

(2) Fuel cells

(3) Thermoelectric generators

(4) Thermionic generators

(5) Heat storage cells

(6) Magnetohydrodynamic induction systems.

(1) Battery-powered weapons systems have been used for at least twenty-five years, but during that period, no significant breakthroughs have been realized. The original lead-acid batteries that were used in World War II torpedo systems have been considerably improved, but further research is required to develop more effective energy-producing reactions than are now available. Typical reactions used to generate electrical energy from batteries are:

$$Mg + 2AgCl \rightarrow MgCl_2 + Ag \text{ in sea water solution}$$

$$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$$

$$Zn + AgO \rightarrow ZnO + Ag \text{ in KOH solution.}$$

Major disadvantages of the storage battery are its lack of endurance and excessive weight. It is necessary to recharge the battery or to replace it when the power supply is exhausted. The first method is time-consuming, requiring as much time off from mission performance to recharge the equipment as time applied to the accomplishment of the mission, whereas the second method is too expensive.

(2) Fuel cells, which have been known since 1834, are electrochemical devices in which the chemical energy of conventional fuels is converted directly into low-voltage direct current. See Figure 11 for a schematic diagram of a fuel cell and its use in a power plant. Such a power source has the basic elements of a battery; i.e., positive and negative poles and an electrolyte or other ion-transport medium.

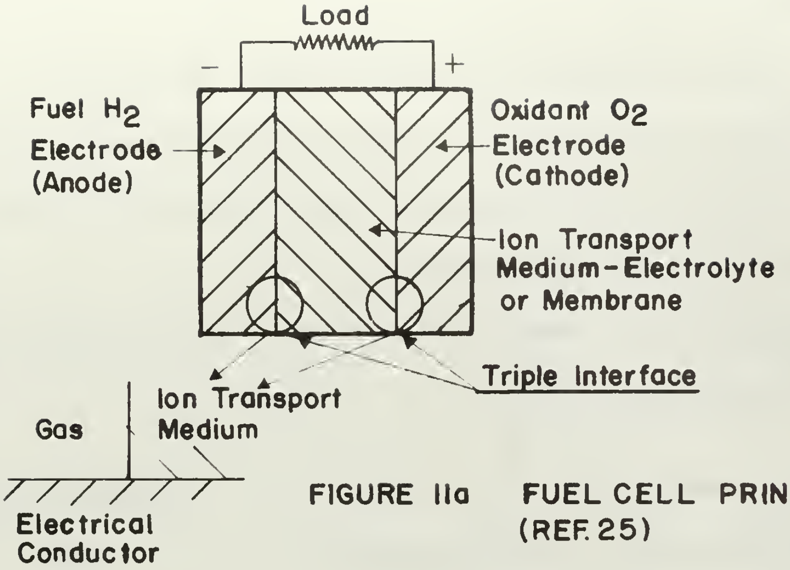


FIGURE 11a FUEL CELL PRINCIPLE (REF. 25)

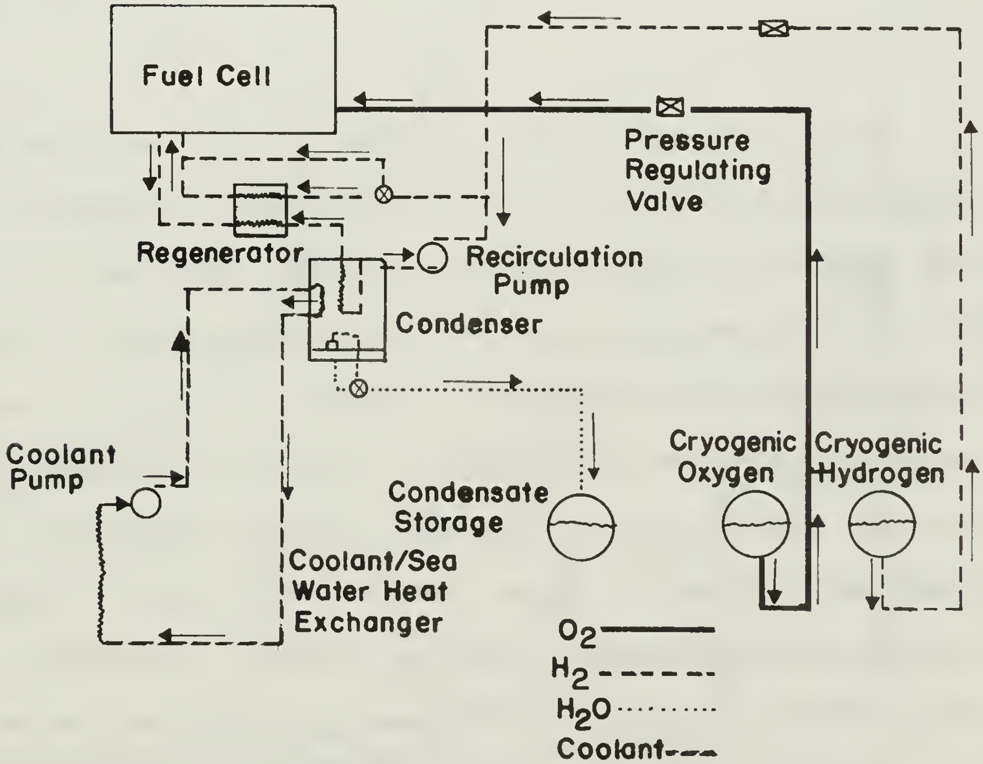


FIGURE 11b REPRESENTATIVE FUEL CELL POWERPLANT (REF. 25)

However, unlike the ordinary battery which stores energy to be converted in the cell, the fuel and oxidant are fed continually to the fuel cell from an external source. The fuel cell is not limited by a Carnot cycle, and its conversion efficiency is quite high since the only limit is the ratio of free energy of reaction of two chemicals to the total heat of reaction.

Kinsinger[25] compares the overall efficiency of the fuel cell to more conventional sources:

POWER PLANT	OVERALL EFFICIENCY
Boiler-steam turbine generator	30%
Diesel generator	35%
Gasoline generator	18%
Fuel cell	65%

Many types of fuel cells are being developed using various fuels, electrodes, catalysts, and electrolytes and ranging over a wide spectrum of temperatures and pressures. Most fuels are basically hydrogen, cryogenically generated from ammonia, methanol, JP-5, hydrazine, or cyclohexane; sodium-amalgan is also used. The oxidant used most often is oxygen from liquid oxygen or air; also, hydrogen peroxide can be used. Studies now available show that the cryogenically stored reactants, hydrogen and oxygen, are the optimum fuel cell power plant systems for deep-submergence vehicles. Figure 12 and Table III compare the performance of fuel cell devices with conventional batteries.

(3) Thermoelectric generators make use of the thermocouple principle wherein a potential difference results when a temperature difference is maintained between the joined ends of two materials of dissimilar composition, known as N-type and P-type. When the circuit

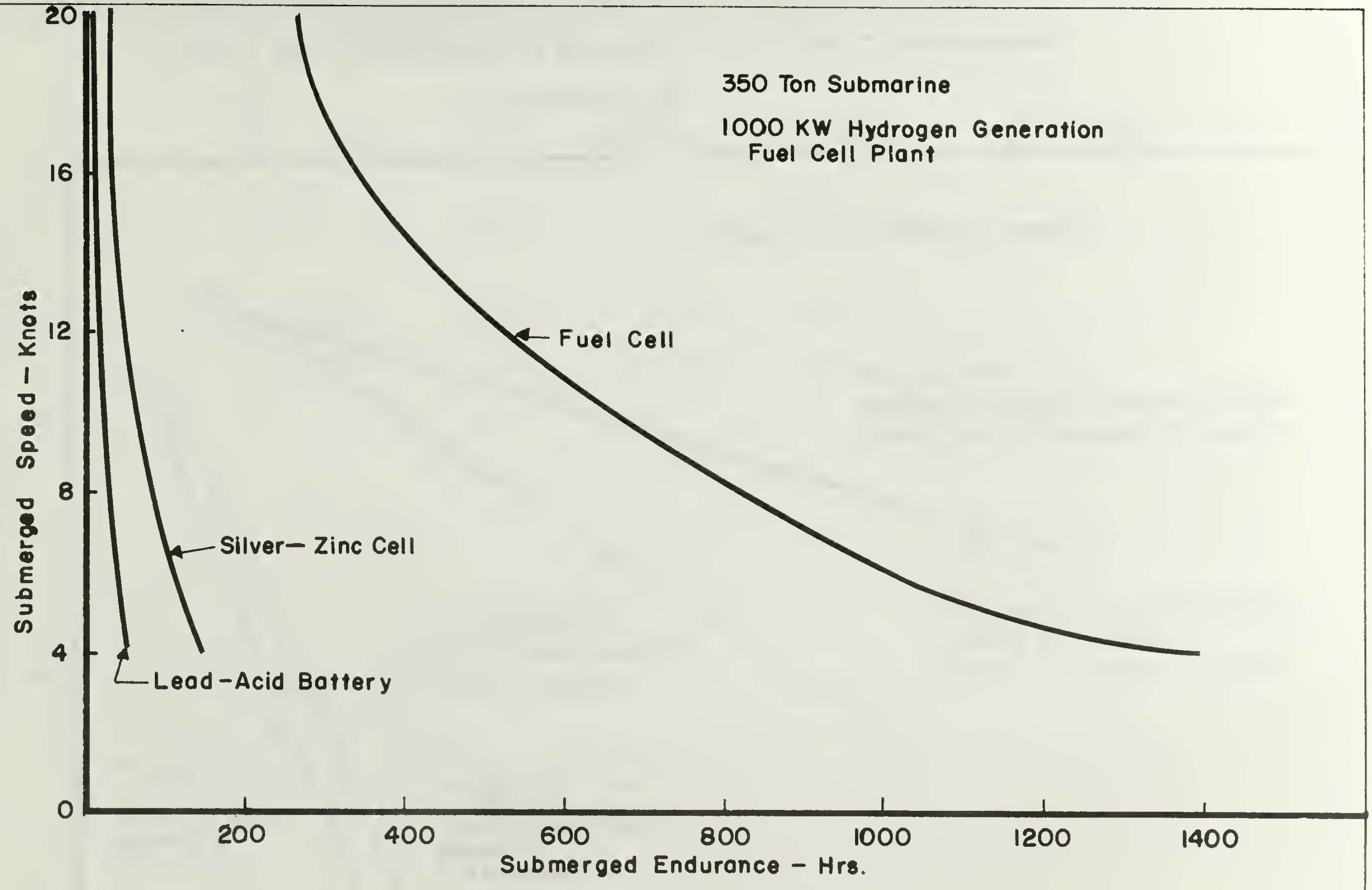


FIGURE 12a COMPARISON OF BATTERY AND FUEL CELL PERFORMANCE (REF. 25)

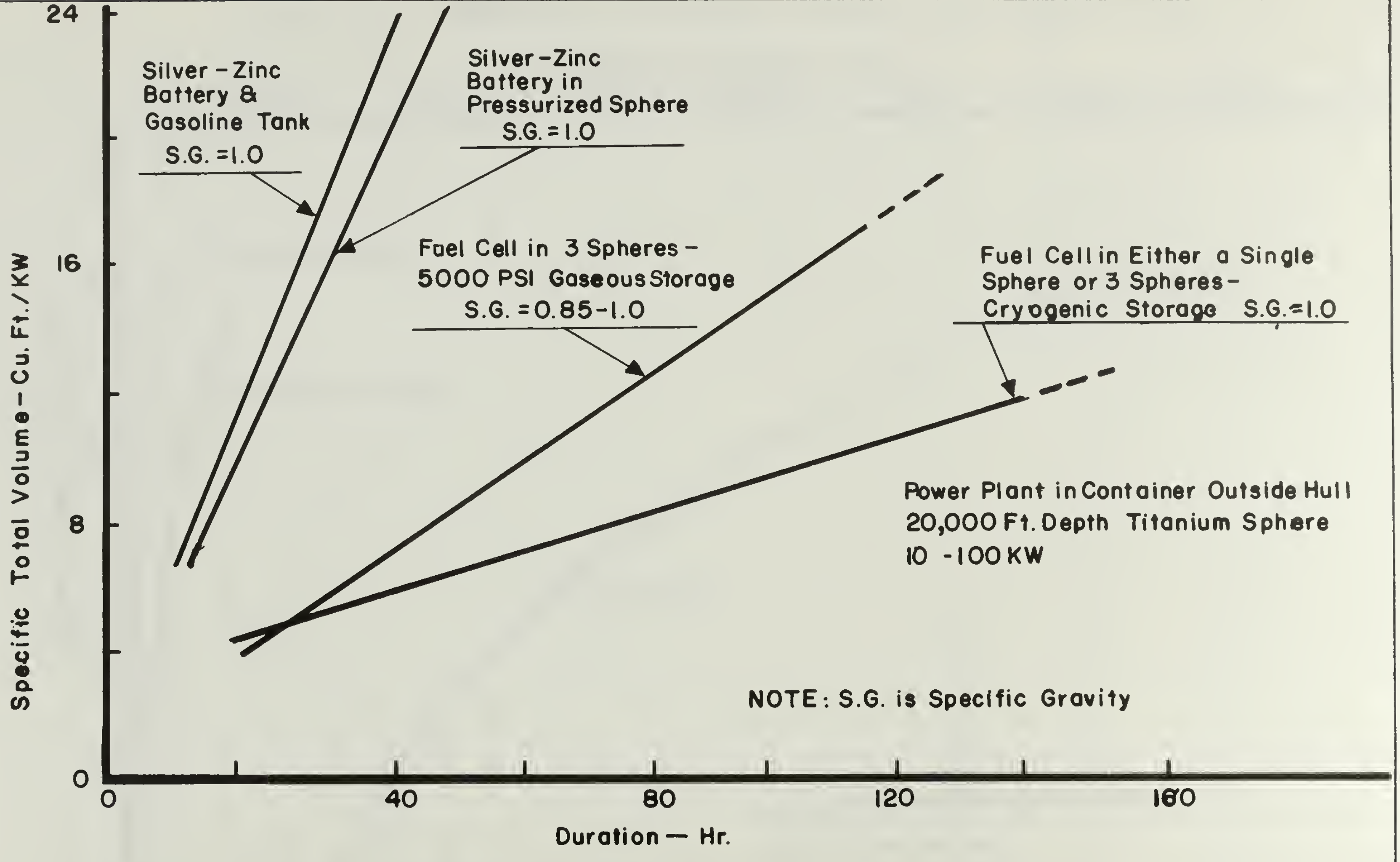


FIGURE 12b COMPARISON OF BATTERY VS FUEL CELL PERFORMANCE (REF. 25)

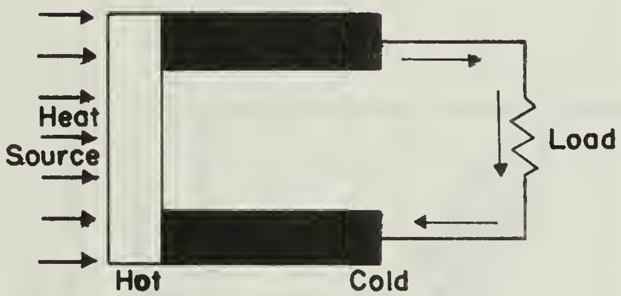
TABLE III. COMPARISON OF PERFORMANCE PARAMETERS FOR BATTERIES AND FUEL CELLS (REF 25)

Power Plant	Power Range (KWH)	Speed Range (Knots)	Endurance Range (Hours)	Depth Range (Feet)	Submerged Displacement Range (tons)
Lead-Acid Battery	30-300	1-15	5-24	1000-20,000	3-350
Silver-Zinc Battery	30-900	1-20	5-72	1000-20,000	10-350
Fuel Cell:					
Cryogenic H2 and 02	30-150,000	5-20	5-720	6000-20,000	5-1000
H2 Generator and 02	150,000 to 600,000	5-25	360-1080	6000-20,000	1000-2000

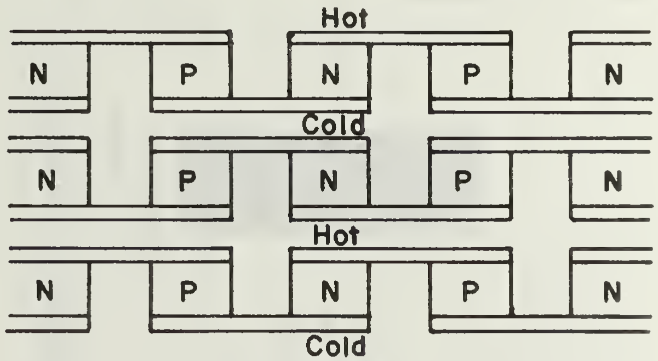
is completed, current flows in the N-type semi-conductor from the cold to the hot end while in the P-type semi-conductor, it flows from the hot to the cold end. See Figure 13a.

Thermoelectric generators are inherently low voltage devices which can generate voltages on the order of 0.1 to 0.2 volts per thermoelectric couple over the feasible temperature ranges. Thus, a large number of couples must normally be connected in series to produce a usable voltage as shown in Figure 13b. Thermoelectric generators with capacities ranging from a few watts to 500 watts have been developed, but their use as large power sources is not yet feasible.

(4) Thermionic generators are essentially an extension of the electron tube consisting of a cathode which emits electrons when heated and an anode which collects the electrons, as shown in Figure 14. A vacuum or an ionized gas space separates the electrodes. The electrons in the vacuum tend to retard the migration of other electrons from cathode to anode. However, if a metal such as cesium is introduced in the form of a low pressure metallic vapor, the positively charged cesium ions serve to effectively neutralize the retardation process and result in higher power densities at lower emittor temperatures. This mixture of electrons and ions is known as plasma, and these converters are called plasma diodes. Figure 14b shows power densities available today. Thermionic generators have similar disadvantages to the thermoelectric generators in that they provide low voltages requiring many converters in series or series-parallel. They have low reliability and need higher operating temperatures than the thermoelectric generators. Nuclear reactors

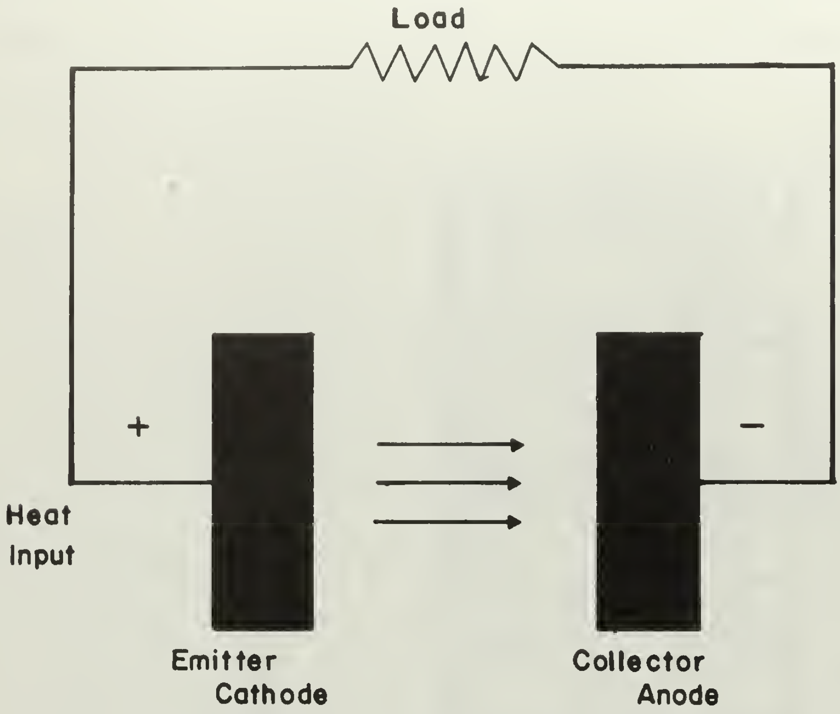


a. PRINCIPLE OF THERMOELECTRIC GENERATOR

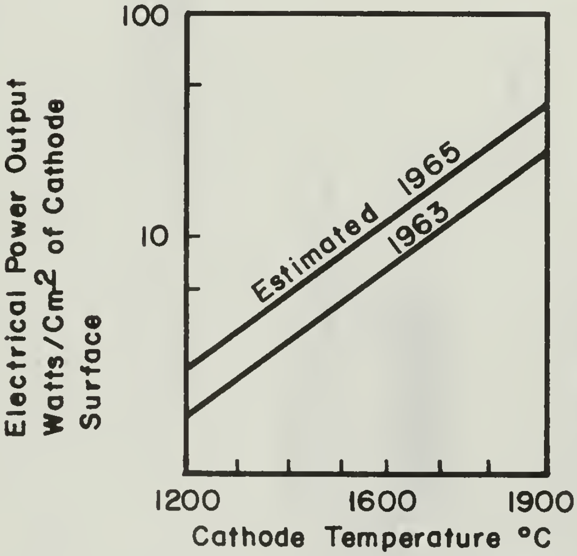


b. PILE OF THERMOELECTRIC ELEMENTS

FIGURE 13 THERMOELECTRIC GENERATOR
(REF. 25)



a. PRINCIPLE OF THERMIONIC GENERATOR



b. PERFORMANCE OF THERMIONIC CONVERTERS

FIGURE 14 THERMIONIC GENERATOR
(REF. 25)

would be ideal heat sources for a thermionic generator. Such devices are not operational as yet, but the Air Force has constructed and tested a three-converter module. These systems possess great potential for future applications, but considerable work is needed on reliability, life, reproducibility, and similar properties.

(5) Heat storage cells are thermal energy storage systems which use materials having a high specific heat or high heat of fusion, or both. These materials are melted by various means such as electric immersion heaters and are stored at a sufficiently high temperature to operate a heat engine or other energy conversion device with good efficiency. Some of the usable materials for this application are lithium hydroxide, lithium hydride, lithium fluoride, and aluminum oxide. Temperatures are normally in the range from 800 to 2780 deg. F, and the average engine thermal efficiency, when operating between 800 and 1200 deg. F, is 25 per cent.

(6) Magnetohydrodynamic (MHD) induction systems present a more novel approach to the generation of electrical power than the previous methods discussed. Due to the relatively poor electrical conductivity of seawater, an indirect means of utilizing the concepts of MHD has been developed. The specific device proposed by Migotsky and Newringer[215] is shown schematically in Figure 15. It consists essentially of a coil wound around a cylinder, an annulus containing a conducting liquid and a flexible diaphragm which separates the conducting fluid from the non-conducting ambient water. A sinusoidal current is impressed along the coil and results in a pulsating magnetic field which travels along the annulus, inducing ring currents in the conducting liquid. The current and magnetic field interactions produce

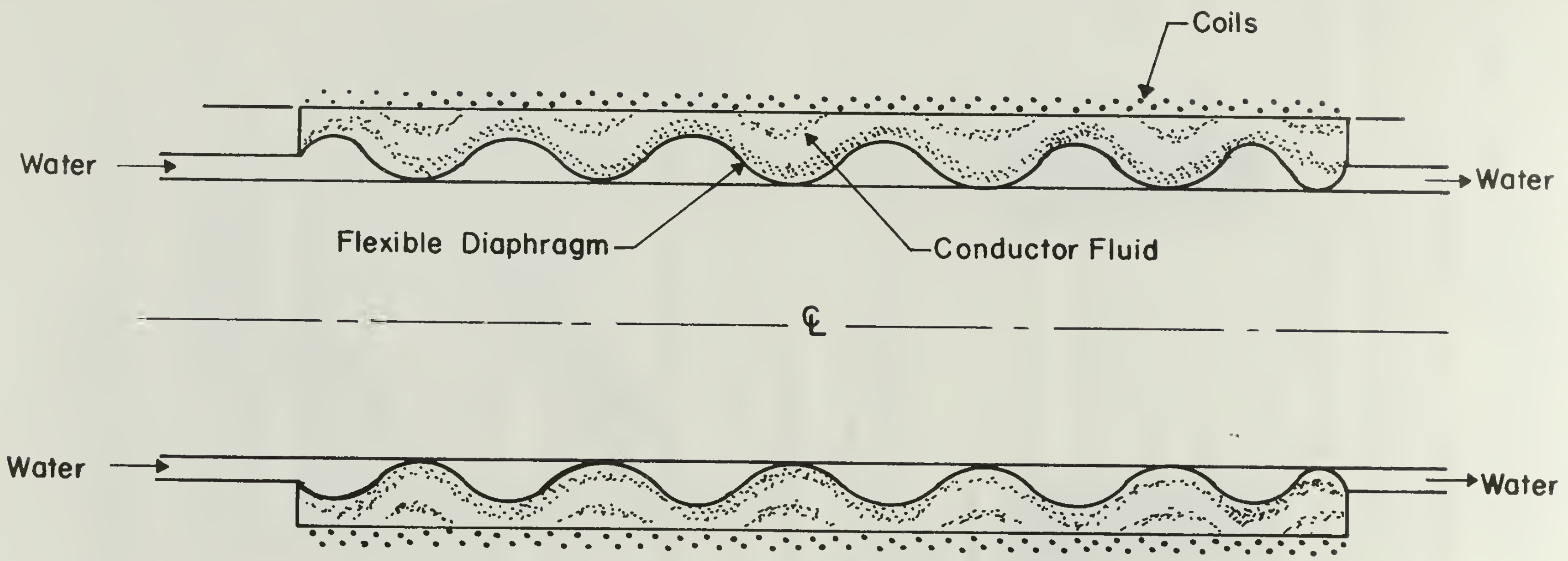


FIGURE 15 SCHEMATIC OF MAGNETOHYDRODYNAMIC INDUCTION COMPRESSOR (REF. 215)

Lorentz forces in the radial and axial directions. An axial pressure gradient is induced in the conducting fluid, and the resulting force pulses tend to "milk" the seawater to the rear, thus producing useful thrust.

Practical application of this ingenious device has not yet been achieved, but its noiseless character is very attractive. The results of the study conducted in Reference 215 indicate that the MHD induction compressor is certainly feasible and potentially capable of propelling marine craft in conjunction with jet thrust systems.

Several of the propulsion units mentioned above in the electric power category involve the use of chemical reactions in producing energy. Normally, however, when discussing thermochemical power sources, we are referring to heat engines such as the turbojet, ramjet, pulsejet, and the rocket. There are a wide variety of power cycles and propellants that can be used in thermochemical plants, many of which have been developed for space applications, but proved suitable for hydraulic propulsion as well. In attempting to find propellants with high energy densities, recent attention has centered on metals, both as slurries in hydrocarbon and water carriers and as direct reactors with seawater. Aluminum and potassium are water reactive metals which yield high temperature gases for power production by expansion.

Many factors must be considered in the use of thermochemical power sources, such as cost, storage of propellants, safety, as well as performance characteristics. Of primary concern in the use of those systems which discharge directly into the surrounding water, is the solubility or condensibility of the products of combustion.

Because of the possibility of the production of non-condensible products, the use of chemical power is more suited to shallow depths or surface vessels where the higher speeds mean more efficient operation, and the need for a condensuctor is eliminated.

Although mechanical power plants are usually proposed as a separate category when listing the various energy sources, their meager use and value do not warrant an extensive discussion. The flywheel device and energy-storing spring are examples of machines which are possible energy sources, but due to their low power production, are not seriously being considered for marine propulsion applications.

The nuclear power plant, which has been developed in a thorough fashion for use on long endurance-type underwater missions and currently is used in surface ship applications, is also being considered as a power source for deep submergence vehicles. Madell[215] investigated the possibility of using nuclear power plants for small, oceanographic research vehicles, which would operate at or close to 20,000 feet below the sea surface. Figure 16 shows a typical nuclear reactor energy producer as it would operate in a typical cycle.

The use of the nuclear reactor for jet propulsion has been investigated in the Rover program which has seen a series of Kiwi and Nerva reactors tested successfully. The latest reactor, the Phoebus-1B, has recently undergone tests and the results indicate that great progress in the field of nuclear jet propulsion has been made. Ground testing continues and new nuclear rocket engines are being developed while clearance for operational tests is pending.

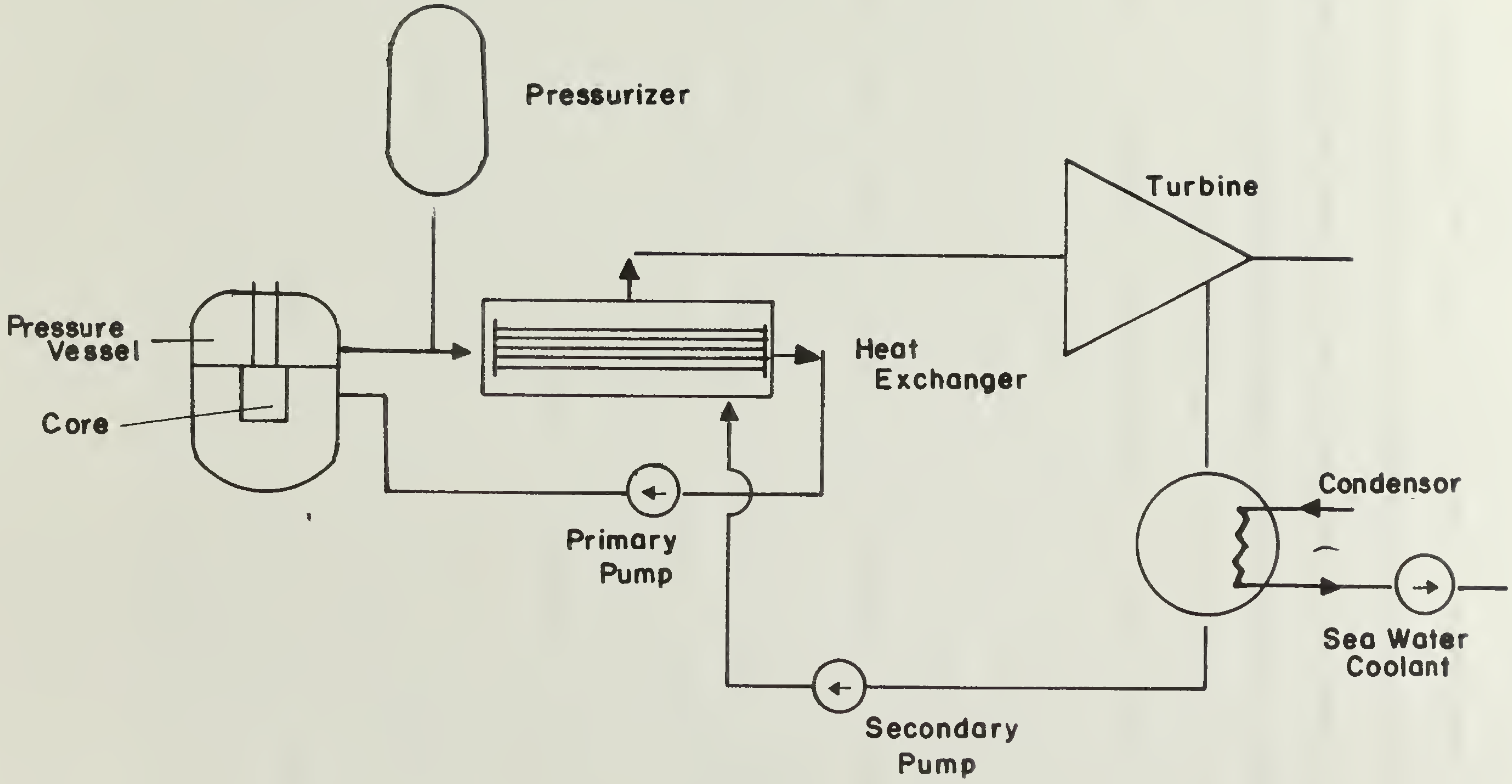


FIGURE 16 SCHEMATIC DIAGRAM OF NUCLEAR REACTOR POWER PLANT (REF. 215)

Obviously, there exist a wide range of possible energy sources available for use with the various marine propulsion systems operating today. Each system has advantages and disadvantages, and selecting an ideal power plant to match the mission and vehicle is an involved process where many diverse criteria must be examined. Kinsinger[25] provides a list of the most influential parameters for selecting a proper power source for deep submergence vehicles.

CHAPTER 3

ANALYSES OF INDIVIDUAL ROTATING PROPULSORS

Having reviewed the basic principles and established definitions for the general performance parameters of a propulsion system, it is now possible to apply these concepts in analyses of the individual thrust devices themselves. Adhering to the classification guide lines suggested previously, the two general categories of rotating and jet propulsors are subdivided into the various mechanisms that have evolved due to technological advances. In each instance, a description of the device and basic method of operation will be followed by an analysis deriving the thrust, torque, efficiency and thrust augmentation parameters, where applicable. When problem areas arise, such as cavitation or noise reduction, the discussion of the proposed solutions will be presented. Graphs demonstrating typical performance characteristics of the thrust units are presented to assist in the comparison.

3.1 CONVENTIONAL SHIP SCREW

The obvious place to begin a discussion of the individual devices used for the propulsion of marine vehicles is with a consideration of the conventional propeller or ship screw. Propellers have been used for over a century as a device for developing thrust, and today there exist many modifications of the original device appearing as a result of continuing research into the basic performance of the simple screw. Hazleton[200] gives a brief history of the development of the ship screw.

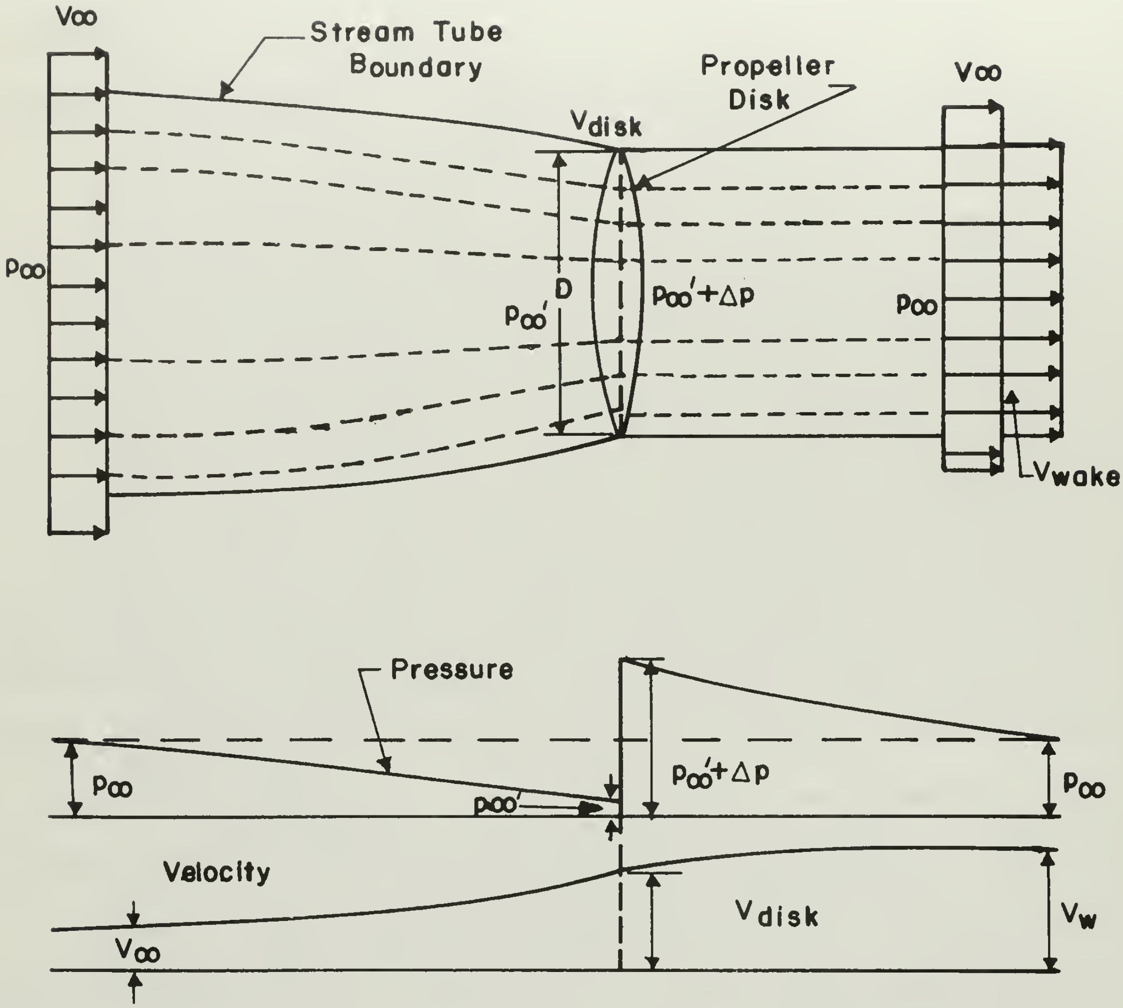
The word, "simple", as used here, is a relative term inasmuch as no completely satisfactory analytical method of predicting propeller characteristics has yet been developed. All the existing mathematical models that have been offered involve oversimplifying assumptions that require large empirical corrections. In addition, the interaction of the flow field around the submerged body and the propeller is only qualitatively understood. The unsteady pressure field and fluctuating thrust and torque developed by a propeller behind a surface vessel or submerged body provide forces and moments that excite vibrations. These problems are not yet completely solved. Often the conventional propeller is not entirely satisfactory for various ship applications; and, therefore, the use of ducted propellers, cycloidal propellers, supercavitating propellers, and the like, form a natural evolution of improvements which can be used in various applications.

A hydrodynamical theory of the screw propeller is today primarily based on the vortex theory proposed and developed by A. Betz and L. Prandtl as far back as 1919[40,73]. However, the application of the lifting-line theory to propellers is far more complicated than for the case of airfoils. The original analysis has been modified in recent years by the induction-factor theory developed by Moriya[74] and Lerbs[74,161]. Still more sophisticated analyses are possible with a lifting-surface theory which yields an integral solution. Only the advent of modern high speed computers has permitted a numerical solution with this complex approach. The success of these analyses has opened up a promising future for the use of various types of propeller systems in more complicated cases, such as cycloidal propellers, tandem propellers, contra-rotating propellers, vertical-axis propellers, supercavitating propellers, and ventilated propellers.

One of the simplest and yet quite useful theories of propeller blade action is the slipstream momentum, or "actuator disk" theory, which was originally developed by Rankine in 1865. Froude, a contemporary of Rankine, also worked on this principle and made notable contributions to the theory[73]. The actuator disk concept is arrived at by picturing a propeller with an infinite number of blades. As Rauscher[41] visualizes it, the only apparent motion of the propeller, as seen by an observer moving forward with the propeller, is the turning of the blade which resembles a blurred disk if the rotation is rapid enough. In this analysis, the propeller is treated like a circular disk of the same diameter as the propeller. It produces a uniformly distributed force on the fluid passing through it, resulting in an increase in pressure of the fluid. The slip-stream, in turn, reacts on the disk with an equal and opposite force, thrusting the body forward through the fluid. Figure 17 shows the general relationships existing in the flow as they are developed using the one-dimensional momentum theory.

The assumptions made in the application of this theory are as follows:

(1) The streamlines are considered continuous and steady through the disk which implies that the axial velocity is the same immediately in front of and immediately in back of the disk.



D = Propeller, or Disk, Diameter

V_∞ = Free Stream Velocity of Fluid

p_∞ = Free Stream Pressure of Fluid

p_∞' = Pressure in Front of Disk

$p_\infty' + \Delta p$ = Pressure at Rear of Disk

V_d = V_{disk} = Velocity at Disk

V_W = V_{Wake} = Velocity in Wake

FIGURE 17 GENERAL FLOW RELATIONSHIPS THROUGH PROPELLER USING ACTUATOR THEORY (REF. 69)

(2) The fluid is perfect; i.e., inviscid and incompressible, indicating that no rotation or twist is imparted to the fluid passing through the disk and, in turn, there is no torque on the disk.

(3) All the velocity increments are small enough to allow for neglect of compressibility effects.

(4) The disk has zero thickness.

As shown in Figure 17, the flow in the upstream region has velocity V_∞ which increases to V_d at the disk and has a final value of V_w in the wake. The uniform free-stream pressure, p_∞ , decreases to p_∞' at the front face of the disk and is incremented to a value of $p_\infty' + \Delta p$ at the rear of the disk. The pressure then returns to its initial free-stream value in the wake. The flow is regarded as potential in nature except for the slipstream that flows through the actuator disk.

The thrust T, which is the force exerted on the propeller by the flow, may be evaluated by the momentum flux method. This is a similar procedure to the general development of the basic thrust equation as set forth in Chapter 2 and only the main relationships will be shown.

Recall that the net force is given by the net momentum flux out of the system boundaries, and since the control surface is everywhere subjected to ambient pressure, the only force is that of the propeller on the fluid (which is equal in magnitude to the thrust). Thus

$$T = A \rho V_d (V_w - V_\infty), \tag{19}$$

where A is the disk area $\pi D^2/4$, ρ is the medium density, the mass flow through the disk is equal to $A\rho V_d$, and V_w is the velocity in the wake. See Figure 17.

By Bernoulli's Equation, the total pressure, $p_\infty + (\rho V_\infty^2/2)$, is constant along a given streamline. However, since energy is added at the disk in the form of work done by the propeller on the fluid, this equation cannot be applied directly across the disk, but may be applied separately in front of and in back of the disk as follows:

behind the disk,

$$p'_\infty + \Delta p + \frac{1}{2}\rho V_d^2 = p_\infty + \frac{1}{2}\rho V_w^2, \tag{20}$$

in front of the disk,

$$p_\infty + \frac{1}{2}\rho V_\infty^2 = p'_\infty + \frac{1}{2}\rho V_d^2. \tag{21}$$

Substituting eq. (20) into eq. (21), we obtain for

Δp = (pressure behind disk) - (pressure in front of disk).

$$\Delta p + \left[p_\infty + \frac{1}{2}\rho V_\infty^2\right] = p_\infty + \frac{1}{2}\rho V_w^2$$

or

$$\Delta p = \frac{1}{2}\rho\left(V_w^2 - V_\infty^2\right).$$

The thrust may be expressed as $A\Delta p$, where Δp is the difference in static pressure between the back and the front faces of the disk. Thus,

$$T = \frac{A\rho}{2}\left(V_w^2 - V_\infty^2\right), \tag{22}$$

or combining eqs. (19) and (22), gives the relation

$$V_{disk} = \frac{V_w + V_\infty}{2} . \tag{23}$$

This relationship can be interpreted in the following manner: Half of the final wake velocity increment is imparted to the fluid before the disk and half behind the disk. This fact is not intuitively nor immediately evident.

Due to the assumptions of this theory; namely, no viscous properties in the fluid and, thus, no rotational motion at the disk, it is not possible to formulate a torque expression at this point; however, following the discussion of the simple blade element theory, a torque parameter will be developed.

The ideal propulsive efficiency of the propeller is:

$$\eta_P = \frac{\text{useful work done by thrust}}{\text{total work done on the fluid}} .$$

The useful work done by the thrust of the fluid is T V_∞, while the work done by the propeller equals the increase in kinetic energy in the fluid:

$$\text{K. E. increase} = \left(\tfrac{1}{2} A \rho V_d\right)\left(V_w^2 - V_\infty^2\right);$$

therefore, using eqs. (22), (23) and the definition of ideal propulsive efficiency given above,

$$\eta_P = \frac{T V_\infty}{\frac{1}{4} A\rho \left(V_w + V_\infty\right)\left(V_w^2 - V_\infty^2\right)}$$

$$\eta_P = \frac{A\rho \left(V_w^2 - V_\infty^2\right)\left(2 V_\infty\right)}{A\rho \left(V_w + V_\infty\right)\left(V_w^2 - V_\infty^2\right)}$$

$$\eta_P = \frac{2 V_\infty}{V_w + V_\infty} = \frac{2}{1 + V_w / V_\infty} .$$

or

$$\eta_P = \frac{2\nu}{1 + \nu},$$

where ν is the effective speed ratio, V_∞ / V_ω. This is the same result as that given by eq. (16) in the general propulsion system development. Eliminating the final velocity, V_w, from the above equations, we obtain:

$$\frac{T}{2\rho V_\infty^2 A} = \frac{1 - \eta_P}{\eta_P^{\,2}}. \qquad (24)$$

Figure 18 contains a plot of the ideal propulsive efficiency, η_P, versus the dimensionless thrust ratio, $C_T = T/\frac{1}{2}\rho V_\infty^2 A$, which can be used for a qualitative analysis of how the ideal propulsive efficiency, η_P, varies with thrust velocity and the area of the disk, or screw diameter.

From Figure 18 we see that for a small diameter propeller causing a high wake velocity (or as we shall see later, a high velocity jet in the case of the pumpjet) and necessarily supplying high thrust for high forward speed, the propulsive efficiency can be predicted as exceedingly low. These considerations indicate that the diameter D should be as large as possible, but the loss due to friction increases as D becomes greater and so, D must be limited, in this sense.

The test results plotted as the actual propulsive efficiency curve in Figure 18 point out that the idealized trends do hold true after the velocity point of maximum efficiency is reached. The ideal value of efficiency for a propeller is never attained because of the additional losses due to:

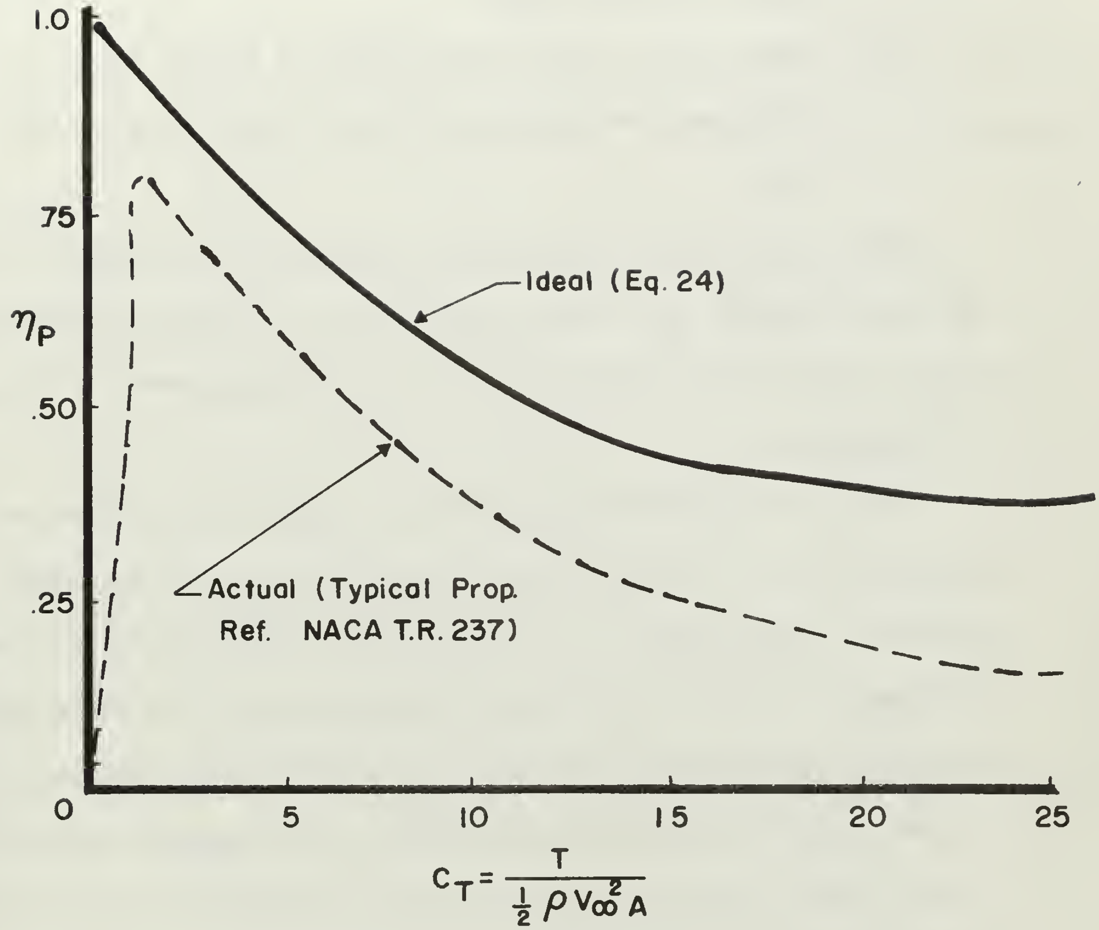


FIGURE 18 ACTUAL AND IDEAL PROPULSIVE EFFICIENCY VARIATIONS (REF. 69)

(1) The rotational energy of the wake due to torque.

(2) Profile drag or friction of the propeller blades moving through the medium.

(3) The fact that thrust is not actually uniform over the disk area, but rather falls off due to tip losses and hub losses.

(4) Losses due to the finite number of blades and consequent variation of thrust at any one point of time.

These losses imply that power would still be required to rotate the screw even at zero thrust, and, thus, the actual efficiency curve drops to zero as the ideal efficiency approaches unity in the graph of Figure 18.

The actual propeller efficiencies obtained throughout the working range are usually from 80 to 88 per cent of the ideal efficiency. The ratio of the actual to the ideal efficiency can be taken as a measure of how well the propeller is working under the given conditions. The fact that the efficiency depends only on the ratio of the velocity imparted to the fluid by the propeller to the forward velocity of the propeller itself is a most interesting fact which will be referred to again in the discussion of water-jet propulsors and their efficiencies.

Although the momentum theory is simple and helpful in determining the ideal efficiency of propellers, it does not take into consideration several important factors; such as, the drag of the propeller blades, the energy loss due to rotational flow, compressibility losses, blade interference and finite blade thrust losses. The momentum theory does not allow prediction of the torque, thereby furthering the necessity to introduce the blade element theory in order to obtain a more complete account of the action of screw propellers.

In the blade element approach, the blade is considered as a rotating wing which is made up of a number of small elements, each of which follows a helical path. The forces acting on each individual blade section are, in effect, summed, and the resultant thrust and torque per blade is obtained for a given set of operating conditions.

In the simple blade element theory the following conditions are assumed to exist[73]:

(1) The flow around each element is considered as two-dimensional and, therefore, is unaffected by its adjacent element on the blade.

(2) The fluid passing through the propeller has no radial component of velocity.

(3) Blade interference is ignored.

(4) There is no contraction in the fluid flow passing through the propeller.

(5) Normally, in applying this theory, the empirical values for section lift and drag coefficients and other similar foil characteristics, are used directly for propeller blade elements of the same cross-sectional shape.

Using the diagram in Figure 19 and the ordinary terminology of airfoil theory, the following analysis can be made by the blade element theory, subject to the assumptions listed above:

β = Angle Between Blade Element And Plane of Rotation

ϕ = Advance Angle

V_R = Resultant Velocity

$\alpha = \beta - \phi$ = Angle of Attack

γ = Angle Between Lift Vector And Resultant Force Vector dR

dR = Resultant Force

dL = Lift Force $\perp$ V_R

dD = Drag Force Parallel To V_R

dT = Thrust Force Parallel To Axis of Rotation

dQ = Torque $\perp$ Axis of Rotation

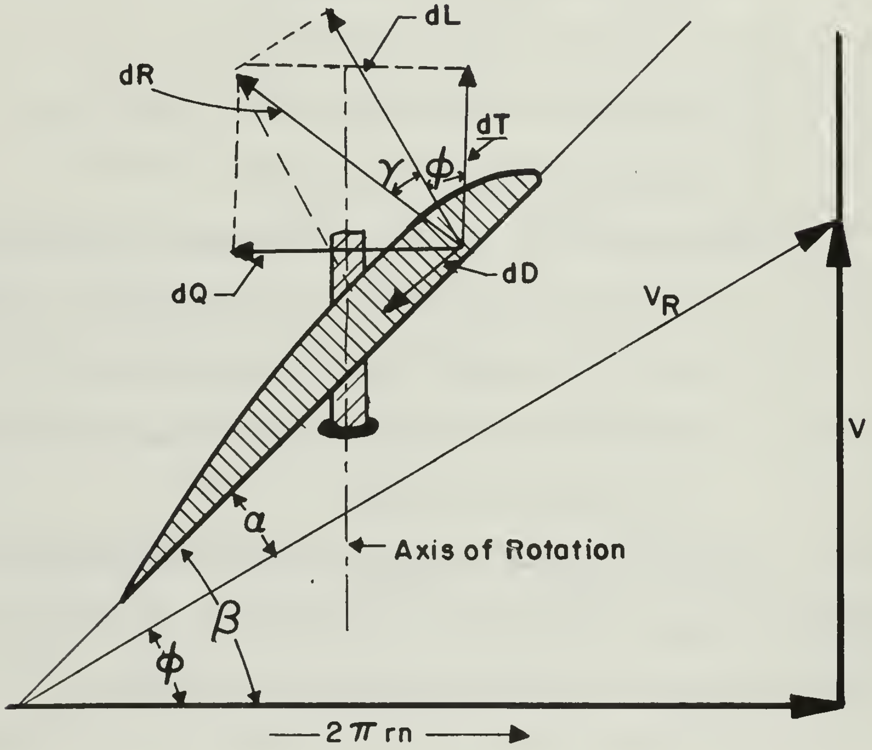


FIGURE 19 BLADE ELEMENT THEORY RELATIONSHIPS ON ELEMENT AT RADIUS r (REF.69)

Consider the blade element at radius r with infinitesimal span dr and chord b as shown in Figure 20. This typical element is located a distance r from the axis of rotation and, hence, has a rotational velocity of $2\pi rn$ (where n is revolutions/second). The forward velocity component V combines with the rotational velocity to give a resultant velocity of V_R along a helical path. Since the blade element is operating at an angle of attack of α, the lift acting on the element is expressed as:

$$dL = C_L\left(\tfrac{1}{2}\rho V_R^2\right) dA = C_L\left(\tfrac{1}{2}\rho V_R^2\right) b\, dr. \tag{25}$$

Using the relationship, $\gamma = \tan^{-1}$ (D/L), (See Figure 19) the total resultant force on the element, dR, is given by

$$dR = \frac{dL}{\cos\gamma} = \frac{C_L\left(\tfrac{1}{2}\rho V_R^2\right) b\, dr}{\cos\gamma}. \tag{26}$$

The thrust of the element is the component of the resultant force in the direction parallel to the axis of rotation, or

$$dT = dR\cos(\phi + \gamma) = \frac{C_L\left(\tfrac{1}{2}\rho V_R^2\right) b\, dr\left[\cos(\phi+\gamma)\right]}{\cos\gamma}. \tag{27}$$

Since $V_R = V/\sin\phi$,

$$dT = C_L\left(\tfrac{1}{2}\rho V^2\right) b\, dr\left[\frac{\cos(\phi+\gamma)}{\sin^2\phi\ \cos\gamma}\right]. \tag{28}$$

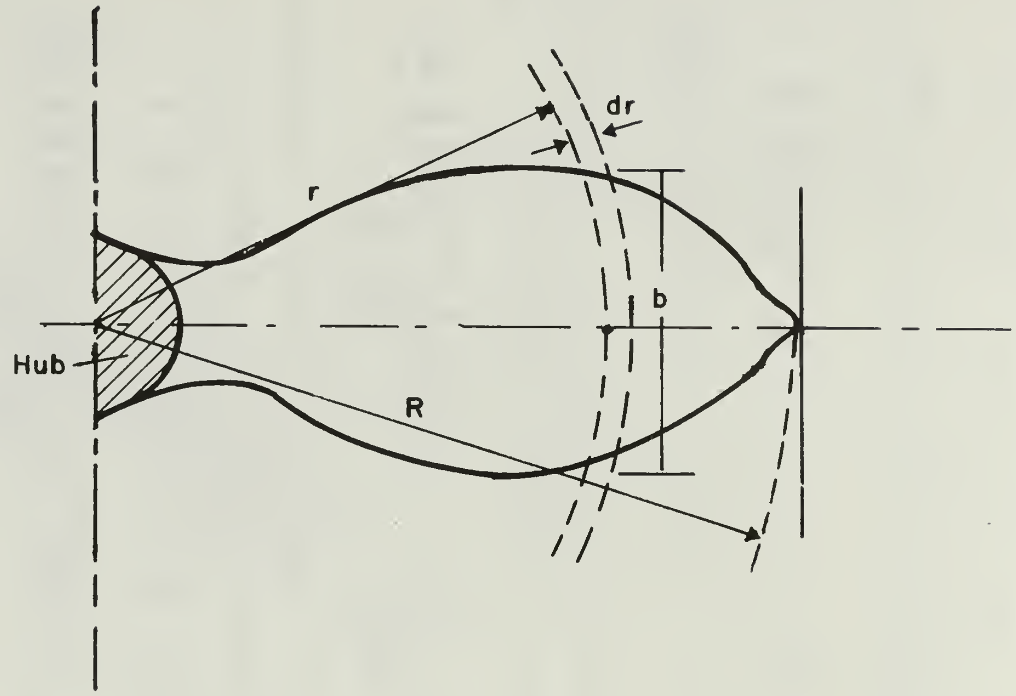


FIGURE 20 DIAGRAM OF PROPELLER BLADE SHOWING BLADE ELEMENT AT RADIUS r

Integrating this differential thrust over the entire blade, the total thrust is obtained:

$$T = \frac{1}{2}\rho V^2 B \int_0^R T_c \, dr, \tag{29}$$

where T = total thrust,

B = number of blades,

T_c = K cos $(\phi+\gamma)$ and

K = $C_L b / \sin^2\phi \cos\gamma$.

Similarly, the tangential or torque force is

$$dF = dR \sin(\phi+\gamma), \tag{30}$$

and the differential torque is

$$\begin{aligned} dQ &= r\,dF \\ &= C_L \cdot \frac{1}{2}\rho V_R^2 \cdot b\,dr \sin(\phi+\gamma)\cdot r \\ &= \frac{1}{2}\rho V^2 \cdot b r\,dr \cdot C_L\left[\frac{\sin(\phi+\gamma)}{\sin^2\phi \cos\gamma}\right]. \end{aligned} \tag{31}$$

Thus, the torque of the entire propeller is

$$Q = \frac{1}{2}\rho V^2 B \int_0^R Q_c \, dr, \quad \text{where} \tag{32}$$

Q = total torque, and

Q_c = Kr sin $(\phi+\gamma)$.

Once the total thrust T and total torque Q are determined, the horse-power absorbed by the propeller or the brake horse-power required to rotate the propeller can be calculated, as well as the ideal propulsive efficiency:

$$\eta_I = \frac{TV}{2\pi n Q}. \qquad (33)$$

An analysis of the efficiency of a specific blade element, usually taken at $r = \frac{3}{4}R$, reveals that

$$\eta_I = \frac{dT \cdot V}{dQ \cdot 2\pi n} = \frac{\tan\phi}{\tan(\phi + \gamma)}. \qquad (34)$$

Equation (34) is misleading in that the ideal propulsive efficiency is not shown to be an explicit function of the coefficient of lift C_L. Actually, for a poorly-designed propeller with low C_L, γ would be large and, hence, η_I would be small. Differentiating this expression with respect to ϕ and equating the result to zero gives the value of ϕ corresponding to the maximum propulsive efficiency, which is found to be:

$$\phi = 45^\circ - (\gamma/2).$$

Since the flow around the propeller is actually three-dimensional and continuous, the simple blade element theory, as described above, has its own limitations and involves many variables which require correction factors. Combinations of the momentum theory and the blade element theory have proved to be more effective than either theory separately, but it has become evident that the best results are attainable only through a consideration of the induced velocities.

A theory has evolved using vorticity elements to represent thickness, camber, and three-dimensional flow. By determining the velocity profile induced on the propeller blade as a result of bound and free vortices used to model the properties stated above, the so-called lifting surface theory has eliminated many of the inaccuracies of past methods and serves as a sound basis for propeller design and performance predictions.

Previous theories have been replaced by this lifting-surface theory which resulted primarily from efforts to estimate the precise effects of camber and angle of attack on the propeller, or, in other words, as a result of introducing the exact three-dimensional effect which had been considered infeasible. The momentum theory of Rankine and the lifting-line theories of the early 1920's have evolved into this very sophisticated and complicated analysis which requires the employment of computer programs for proper evaluation of propeller performance. Even with this theory, however, the exact analysis and prediction of propeller behavior is still not possible and empirical data must be supplied to modify the solution.

Many investigators have contributed to the formulation of the lifting-surface theory as indicated by Wu[74]. The primary efforts have been in the area of steady operation of the water screw in a uniform flow. The linearized lifting-surface theory has developed for marine propellers having B identical, symmetrically-spaced blades and is generally based on the small perturbation approximation along with the following assumptions:

(1) The flow is inviscid, incompressible, and infinite in extent.

(2) The free stream is steady, axially-directed and is often considered to depend on only the radius.

(3) The blades are very thin with small camber and incidence.

(4) The lifting pressure field, caused by camber and angle of attack, is represented by a system of bound vortices spread over the plan-form and a trailing vortex system over the helical surface downstream of the leading edge.

(5) The lift is required to vanish at both the outer tip of the blade and at the hub.

(6) The blade thickness can be represented by a source-sink system over the blade surface whose strength is proportional to the slope of the thickness function.

(7) The disturbed velocity induced at the hub is very small and can be neglected in the majority of cases.

The fact that the water screw is usually operating with pulsation in a non-uniform flow, such as the wake of a ship, and often is subjected to heavy load conditions, further complicates its analysis. The unsteady problem, where the strengths and locations of the bound and free vortices are fluctuating with time, is an extremely complex and laborious analysis. It is not considered necessary or worthwhile in this paper to follow closely all the steps in the process, and the reader is referred to the treatises of Wu and Yamazaki (which are both found in Reference 33) for a more detailed treatment of the unsteady propeller.

The reader is also referred to a recent paper by Wu[74] in which he presents an enlightening history of the development of the water screw, including surveys of the numerous investigations in this field. For the purpose of this study, it is sufficient to note that it is possible, as demonstrated by Wu, to superimpose the induced velocities due to the assumed bound and free vortex distributions with the induced velocity resulting from blade thickness effect. By the application of the boundary conditions, the velocity profile for a given water screw can be predicted, and thus the pressures, forces and moments acting on the blades may be calculated. For a thorough discussion of the vortex modeling technique and the complex solution of the unsteady problem, Robinson and Laurmann's text on wing theory is recommended[43].

Following the determination of the vortex velocities, the forces acting on the propeller are found by recalling that the pressure differential between the top and bottom surfaces of the blade is equal to the product of the strength of the vortex and the component of velocity normal to the bound vortex, or to the blade. The forces in the various directions give rise to the familiar thrust and torque expression which were given in eqs. (11) and (14). The propulsive efficiency is

$$\eta_P = \dot{x}_p T / \dot{\theta}_p Q , \tag{35}$$

where $\dot{x}_p$ is the forward velocity of the propeller and $\dot{\theta}_p$ is the rotational speed. Defining the advance speed ratio as

$$J_A = V/nD = \dot{x}_p / \dot{\theta}_p D , \tag{36}$$

the propulsive efficiency can also be written as

$$\eta_P = J_A D(T/Q). \tag{37}$$

As might be expected, the three distinct theories for obtaining performance parameters of the water screw present similar relationships. Representative graphs showing these characteristics are included as Figure 21.

3.2 COUNTERROTATING PROPELLERS

The current demand for greater payloads and increased speeds in marine systems has brought about the need for more efficient propulsive devices. A single water screw, when required to provide the entire thrust for propelling a large displacement surface ship or driving a fully submerged vehicle at high operating velocities, encounters many problems. Among the more serious difficulties that arise are the early inception of cavitation under heavy propeller load conditions and the intense vibrations that are transmitted from the screw to the hull as a result of unbalanced torque. As a possible solution to these problems, counterrotating screws, which are systems of propellers mounted on coaxial shafts and rotating in opposite directions, have been investigated.

Despite the obvious disadvantages of increased complexity and greater weight, due to the necessity of including engine-propeller shafting and gearing, and the design sensitivity of the system, counterrotating propellers have the following favorable properties: (1) Exit losses are diminished, and, hence, efficiency is increased since the rotational energy imparted to the water by the forward propeller is partially recovered by the aft propeller. (2) Torque unbalance can be essentially eliminated while maintaining stability.

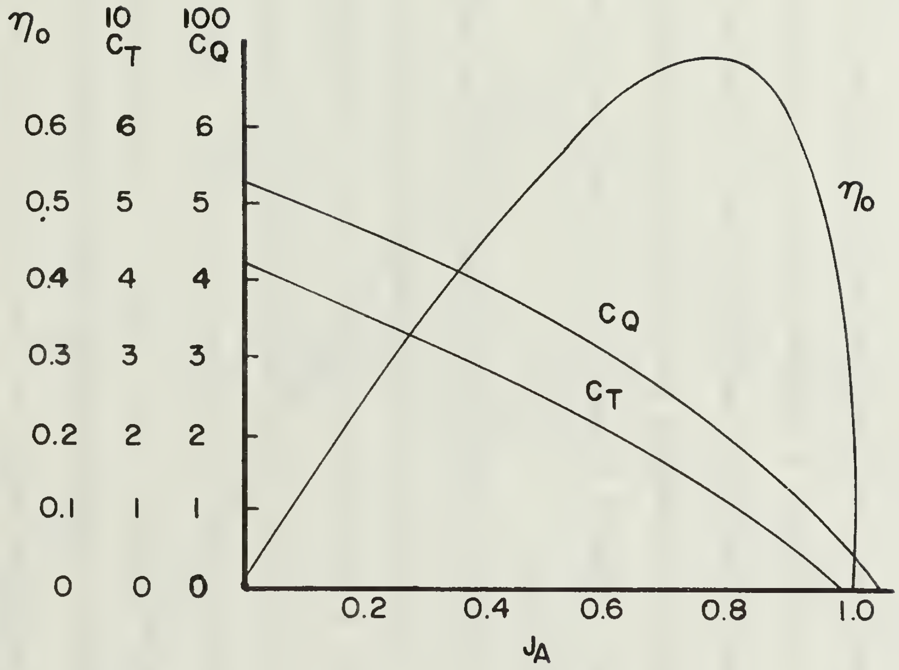


FIGURE 21 TYPICAL VALUES OF PERFORMANCE PARAMETERS FOR CONVENTIONAL PROPELLER (REF. 33)

(3) The average loading per blade is considerably reduced, thus delaying the inception of cavitation and decreasing the chances of cavitation damage to the system.

Several features peculiar to the counterrotating propeller concept should be mentioned in this discussion. The majority of tests conducted have used two propellers; however, the counter-rotating propeller system is not restricted to two elements, but rather may contain as many components as are required for adequate power absorption. Limitations on propeller blade diameters and rotation speeds are other factors which determine the number of propellers to be used. A further aspect in the determination of the proper system for a particular application is the use of a greater number of blades on the rearmost propellers since smaller diameters are required to avoid the tip vortices caused by the forward propellers.

Each individual element of a counterrotating propeller system operates in accordance with the fundamental principles of the single water screw. A theoretical analysis of the flow through a separate element of the system can be accomplished using the methods discussed in the section on the conventional water screw. The primary mode of performance analysis used today is the unsteady three-dimensional vortex theory, or lifting surface theory, in which the induced velocities acting on the blades are evaluated and the resultant forces and efficiencies obtained.

Typical results of the investigations conducted into the counter-rotating propeller concept are shown in Figure 22, which is extracted from Reference[202] by Hecker and McDonald. The results of these tests

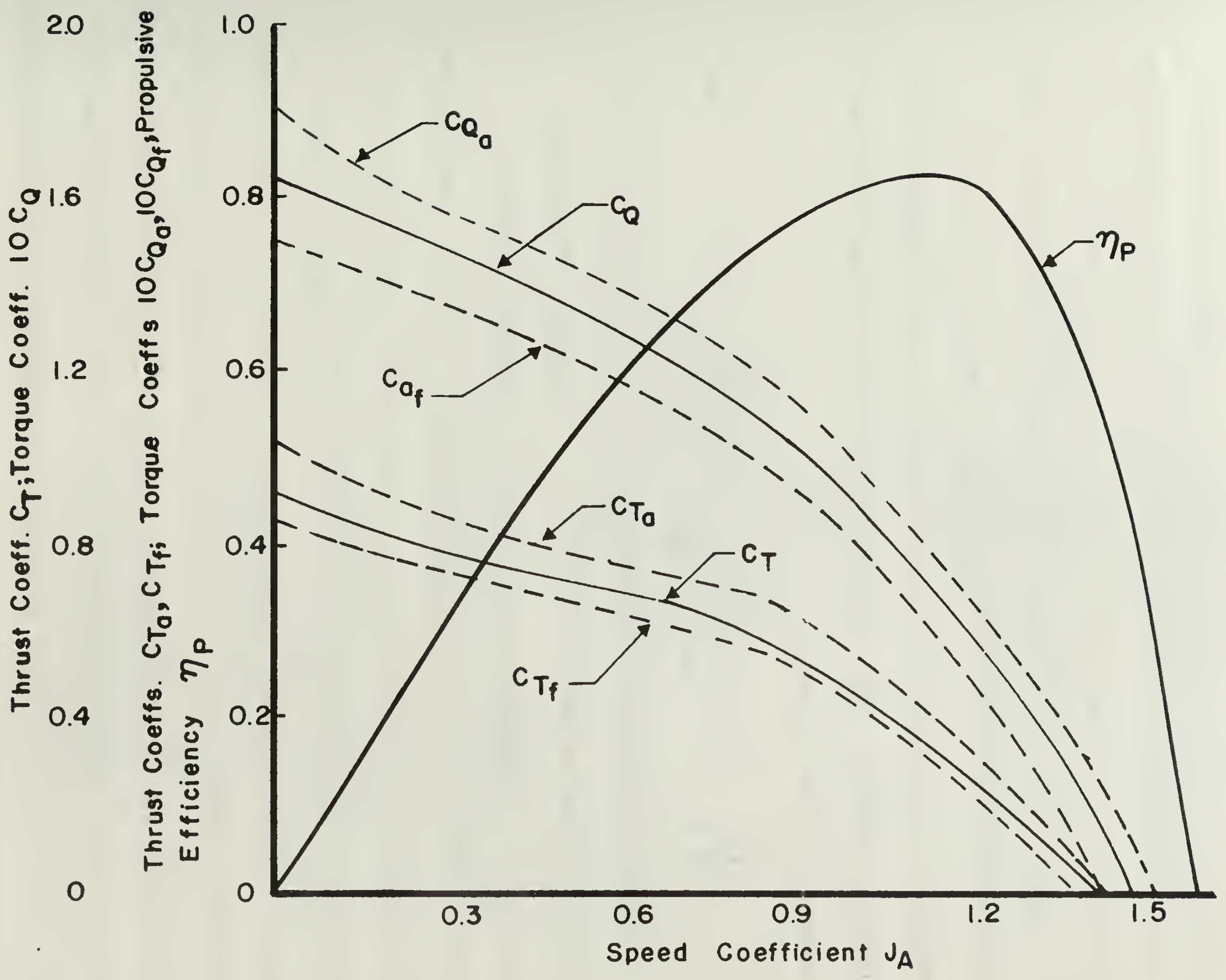


FIGURE 22 TYPICAL PERFORMANCE FIGURES FOR COUNTERROTATING PROPELLERS (REF. 202)

indicate that the efficiency of the propeller systems evaluated was slightly higher than could be expected from single propellers. Further conclusions drawn were that the torque on the two elements was balanced to within 5 per cent and the reduced blade loading cut down on the severity of the cavitation problem. For a proper understanding of the results shown and for comparison purposes, it should be stated that definitions of C_T and C_Q used by Hecker and McDonald are the same as those given in eqs. (11) and (14) with $T = T_f + T_a$, $Q = Q_f + Q_a$ and $D = D_f$, where the subscripts f and a refer to the forward and aft propellers, respectively, and as indicated, the coefficients are all based on the diameter of the forward propeller. The propulsive efficiency of the two-propeller system was given by the relationship

$$\eta_P = \frac{(T_f + T_a)V}{2\pi(Q_f + Q_a)n} . \qquad (38)$$

The Tandem Propeller Submarine (TPS) is an offshoot of the counterrotating propeller scheme and is currently receiving a great deal of attention as an advanced underwater propulsion system. See Reference 200. Figure 23 indicates the location and relative size of the propellers as conceived by this system. As evidenced by the fact that there are several diameters distance between the forward and aft elements in this design, the increased efficiency advantage of the counterrotating system is not the foremost feature in this application. Rather the improved maneuverability of the vehicle due to the unique system of variable-pitch blades is the factor which makes the TPS device so desirable. This system causes the blades to change their pitch during each revolution according to

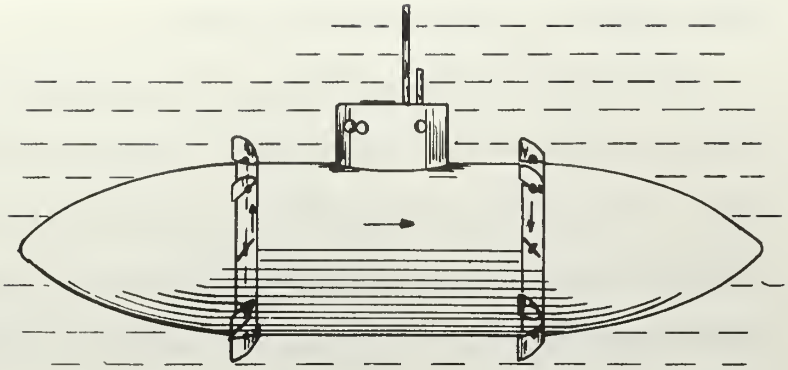


FIGURE 23 DIAGRAM OF TANDEM PROPELLER SYSTEM (TPS) SHOWING LOCATION AND RELATIVE SIZE OF PROPELLERS (REF. 200)

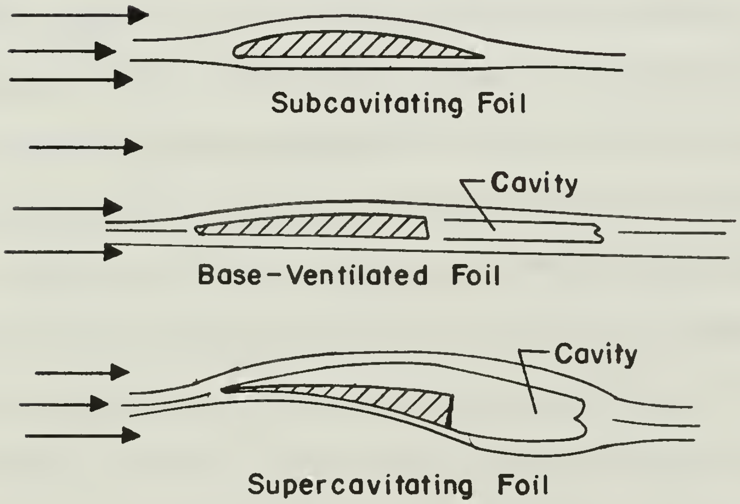


FIGURE 24 COMPARISON OF TYPICAL FLOW CONFIGURATIONS AROUND FOIL SECTIONS (REF. 33)

a planned program. This gives rise to transverse forces and a large degree of freedom control system.

The Tandem Propeller System develops thrust in a manner similar to that of the conventional screw with variable-pitch blades. The use of a large hub-to-diameter ratio in the propeller design is what completely differentiates this system from other counterrotating devices. Using the same definitions for the thrust and torque coefficients and the efficiency parameter as previously stated, Joosen, van Manen and van der Walle conducted a series of tests on propellers with the characteristics of those employed in the TPS concept[33]. The results of these experiments demonstrated that this type of propeller had a maximum efficiency of about 70 per cent, comparable to that of the normal screw.

3.3 SUPERCAVITATING PROPELLERS

As high speed marine vehicles are developed, there will be a great demand for increased thrust from existing propulsive devices. The accompanying need for excessively high rotative speed soon results in a sharp decrease of propeller performance and physical damage to the system due to the onset of cavitation. Although the phenomenon of cavitation is not completely understood, and heavy reliance is placed on empirical data for predicting its occurrence and properties, a brief discussion of the more familiar features of the subject is appropriate at this point.

By definition, cavitation is the formation of partial vacuums or vapor cavities in the flow of a fluid medium which results in the separation of the fluid from the surface over which it is moving. The actual cavities are regions of low pressure where the liquid reaches its vaporization pressure and is transformed into a gas. These cavities cause the designed path of the fluid particles to change and the subsequent forces and movements to be altered from their optimal values.

In addition to the above, the rapid creation and collapse of these cavities on a propeller surface cause noise radiation and blade erosion. Eventually, structural damage and propeller failure result. Cavitation has become a most serious problem in the design of marine propulsive devices and has resulted in the development of supercavitating propellers, so called since they are actually designed to operate under conditions conducive to severe cavitation. "Supercavitating" indicates a flow configuration in which the suction side of the blade sections is completely enclosed within a cavity originating at the thin sharp leading edge of the blade and extending beyond the trailing edge. Figure 24 compares the flow around a sub-cavitating foil, a base-vented foil and a supercavitating foil.

The inception of cavitation on a marine propeller may occur in the hub vortex, at the tip vortices or on the blade itself, depending upon the particular dimensions of the blade. The formation and expansion of cavitation is dependent upon the propeller loading as well as the cavitation number σ_n, which is the ratio of the differential between the ambient and cavitation pressures to the rotative speed term,

$$\sigma_n = (p_\infty - p_c)/\tfrac{1}{2}\rho(nD)^2. \qquad (39)$$

Alternatively, the free stream velocity, V_∞ , is used to define a cavitation number, σ_∞ , where

$$\sigma_\infty = (p_\infty - p_c)/\tfrac{1}{2}\rho V_\infty^2. \tag{40}$$

In general, the spread of cavitation over the blade is expedited by increasing the propeller loading and reducing the cavitation number. Figure 25 shows the effect of cavitation on thrust development. As can be observed from this graph, the rate of increase of thrust with rotative speed diminishes until a point is reached when the entire blade is cavitating. At this time, an increase in RPM might result in a decrease in thrust. In a situation such as this, the cavitation losses completely absorb the additional power being furnished to the propeller. However, following this leveling-off period, the thrust again begins to increase as the rotation speed of the device is increased. This stage of operation is the super-cavitating condition, and its inception is precisely defined as commencing at that angular velocity where the rate of thrust increase with rotative speed is first a minimum, with the forward speed and ambient pressure held constant. Figure 26 depicts typical thrust variations with advance speed ratio $J_A = V/nD$, when the cavitation number based on free stream velocity, σ_∞ , and the cavitation number based on rotative speed, σ_n , are held constant.

Figure 26 indicates possible regimes of operation for a super-cavitating propeller and gives a qualitative meaning to the effects on the blade that could occur as a result of operating in these regimes. A detailed description of the existing conditions in each operating range is presented by Tulin[33]:

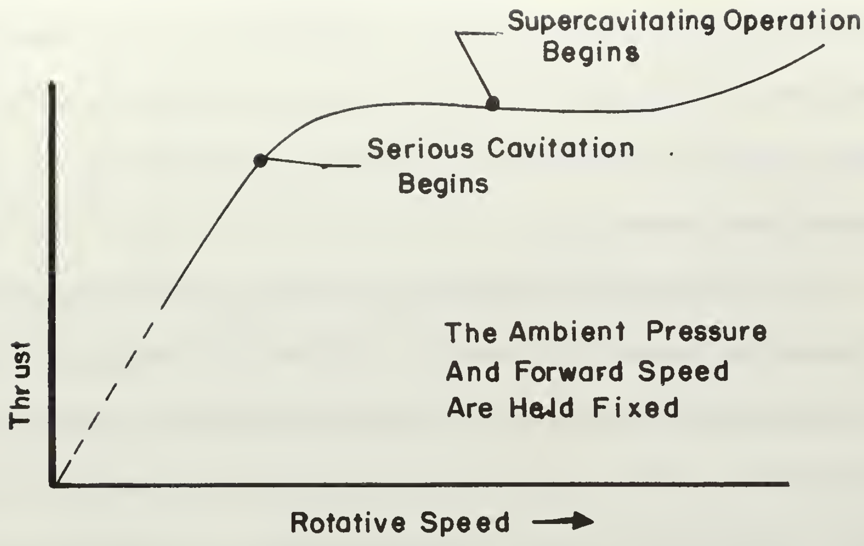


FIGURE 25 CAVITATION DEVELOPMENT AND EFFECT ON THRUST (REF. 33)

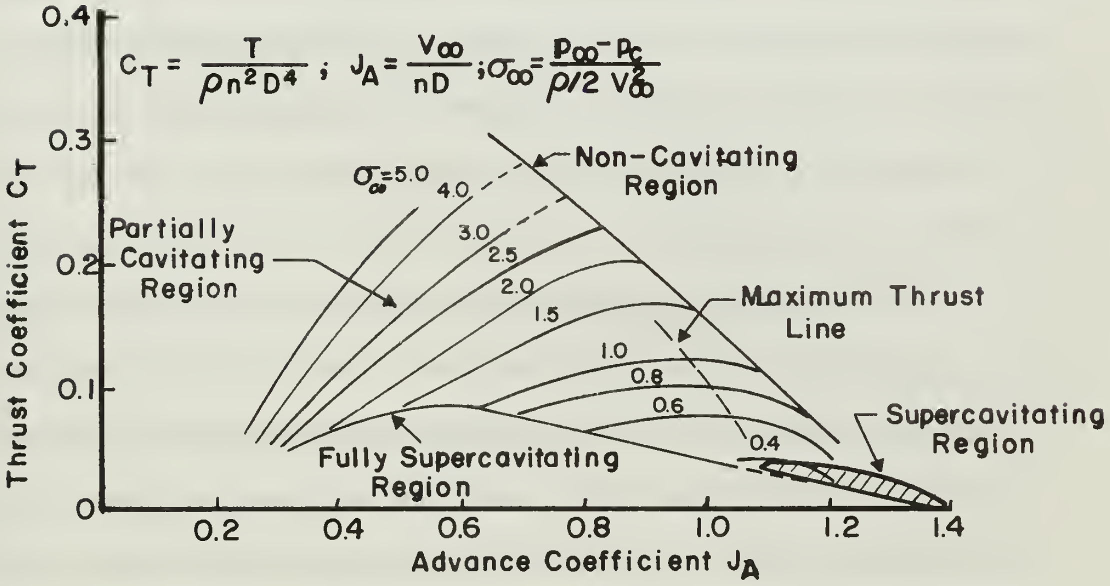


FIGURE 26 TYPICAL THRUST VARIATIONS WITH ADVANCE SPEED RATIO, CONSTANT CAVITATION NUMBER (REF. 33)

(1) Non-cavitating operation is represented by that portion of the plot where no significant cavitation is occurring, and, therefore, the thrust is increasing at a rapid rate with decreasing advance speed coefficient. This is the design line for a simple conventional water screw.

(2) The partially cavitating regime is defined as that range of operating conditions where a considerable amount of cavitation is taking place, but distinct cavitation patterns are not fully established. This region is represented by a family of thrust curves depending on the cavitation number. In general, it has been observed from empirical results that thrust decreases sharply with a decrease in advance coefficient with cavitation number held constant. Also, thrust decreases rapidly as cavitation number decreases with the speed coefficient kept constant. This region is further divided by a maximum thrust line into a regime where the thrust increases with rotative speed and an area where the thrust decreases as rotative speed increases, thus showing the relative effects of cavitation.

(3) The supercavitating regime occurs when all blade elements are operating in supercavitating flow. The cavitation patterns are completely developed and the effectiveness of the blade elements decreased as σ_n decreases, resulting in a loss in thrust. This is represented by a compact family of curves on the thrust-advance speed ratio curve of Figure 26. In this operating region, the effects of interference between the blade and the cavity formed on the preceding blade is very important as are the blockage effects on the flow into the propeller due to the large size of the cavities.

(4) The <u>fully-supercavitating</u> stage is characterized by very low section cavitation numbers. The effectiveness of the blade elements is not altered significantly by decreasing cavitation numbers. This operating region is essentially an extension of the previous region, varying only as to degree of thrust fluctuation with forward and rotative speed. On the graph of Figure 26, this regime is depicted by a single thrust characteristic curve having an arched shape. There are increased interference and cavity blockage effects. High-speed hydrofoils operating at speeds in excess of forty to forty-five knots will be primarily within this latter range of cavitating conditions.

In the case of the subcavitating propeller, which is designed to operate with no cavitation present, the major thrust losses result from the wasted kinetic energy imparted to the wake and from friction of the fluid on the blades. The supercavitating propeller suffers power losses primarily as a result of cavity or pressure drag which is caused by separation of the flow and the apparent increase in camber of the blade. The friction drag along the non-cavitating or lower surface of the blade must be added to the pressure drag and the induced exit losses to obtain the total thrust reduction factor acting on the supercavitating propeller. These induced losses are believed to be much less than those of a subcavitating propeller operating at the same net thrust loading; however, no definitive proof of this fact has been shown and, indeed, the efficiencies of supercavitating propellers have thus far not been as high as those of properly designed subcavitating propellers. The use of supercavitating propellers is dictated by other considerations, such as the elimination of blade erosion, and is not always selected for efficiency reasons.

In order to more fully understand the principles involved in the operation of the supercavitating propeller, we should recall the vortex analysis of the subcavitating or conventional screw made previously. The shed vortex field that exists in the wake of the blade as described in the conventional screw analysis is also present in the case of the supercavitating blade; however, an additional velocity field due to the cavities themselves is important and must be superimposed. This induced velocity field is considered to be a result of the pressure drag caused by the cavities whereas the velocity field present in both systems is attributable to the thrust force. This superposition of induced velocities naturally results in a final velocity profile from which the performance parameters are derived as before.

3.4 VENTILATED PROPELLERS

The use of mixed gas-water flows over the surface of water propellers in a process known as ventilation has recently received a great amount of attention. The efforts in this field are to find a means of bridging the operating gap between the low speed conventional water screw and the supercavitating propeller, which is oriented toward high speed performance. Hoyt and others at the Pasadena facility of the Naval Ordnance Test Station have conducted a series of tests using the ventilation concept[33]. See Figure 24 for a schematic of a base-ventilated foil.

In ventilated propellers, air or other gases are injected into the fluid flow through holes or grooves bored into the blade surfaces. These gases serve to artificially create cavities around the surface and extending behind the blades in a manner similar to that resulting from natural cavitation. Therefore, ventilation can be thought of as a design method for inducing cavities on the blade by simulating the natural effects of cavitation. Two major design techniques have been examined in the ventilated propeller field:

(1) In ventilating a supercavitating propeller, a gas is admitted into the existing vapor cavity, thus reducing the effective cavitation number of the flow and extending the "supercavitating" type of operation over a greater range of speeds, from the lower speeds in the take-off regime to the high speed cruising configuration.

(2) In the base-vented propeller, the blades are not designed for supercavitating flow, but rather have blade sections which are specifically constructed to operate with the gas flows. They have low drag configurations and excellent cavitation resistance qualities when in the ventilated state.

The first method has been proven successful in drastically reducing the noise radiation and virtually eliminates the blade erosion problems caused by the weak portions of the cavity collapsing on the blade. However, as shown in Figures 27 and 28, extracted from reference[33], the ventilated supercavitating propeller has not reached the improved performance level attained by the base-vented propeller. The performance parameters are seen to fall off sharply as the air flow is injected over the blade surface whereas an increase in overall performance is expected from theoretical considerations. A maximum efficiency value of about 70 per cent was achieved at various cavitation numbers in the results presented by Tulin. As the advance ratio was increased, however, a fall off in efficiency was noted. This unexpected event was attributed to the movement of the point of cavity formation from the leading edge toward the rear. Further tests on this technique must be accomplished before a firm performance evaluation can be made.

The alternative technique of devising a special propeller for operation with the ventilation concept has been more successful in realizing performance gains over the conventional screw propeller. An efficiency of over 80 per cent was obtained in tests at the Garfield Thomas Water Tunnel as evidenced by Figure 28. The efficiency was seen to drop off considerably; however, for cavitation numbers below the design value for the propeller tested, thus indicating that heavy cavitation is adversely affecting the base-vented propeller.

3.5 CYCLOIDAL PROPELLERS

Cycloidal propellers are combination propulsion and maneuvering devices which consist, in general, of a circular disk carrying about six or eight elliptically-shaped blades which are located near the periphery of the disk. See Figure 29. The circular base is set flush with the bottom of the vehicle to be propelled, and only the blades protrude downward into the water. The entire assembly revolves about a central vertical axis while, simultaneously, each individual blade executes an oscillating motion about its own separate spanwise axis. It is the combination of orbital and oscillating motion that accelerates the flow in a definite direction and produces thrust.

The path of each blade axis describes a cycloidal path through the water regardless of the particular blade motion or orientation and, hence, the name "cycloidal" is used to describe this type of propulsor. In simple terms, a cycloid is the path traced by any point in the plane of a circle when that circle rolls without slipping along a straight line.

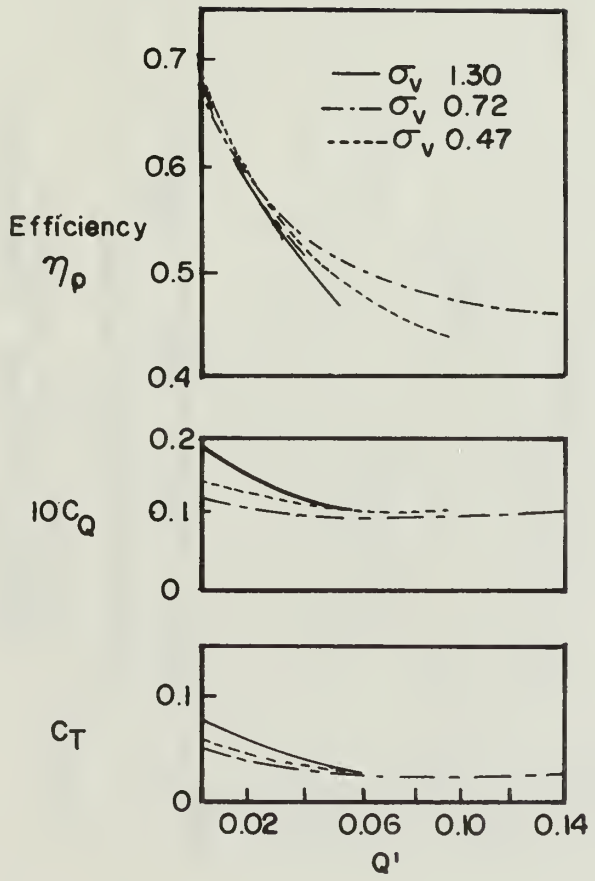


FIGURE 27 EFFECT OF AIR-FLOW ON PERFORMANCE OF VENTILATED SUPERCAVITATING PROPELLER (REF. 33)

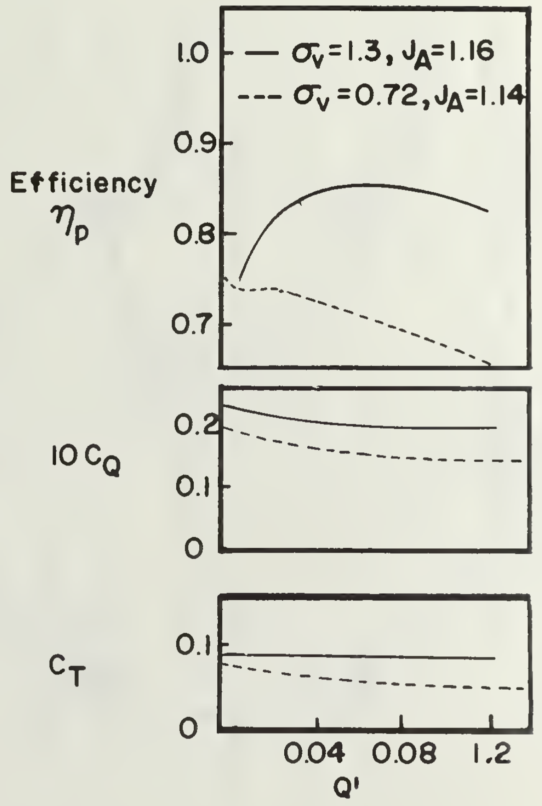
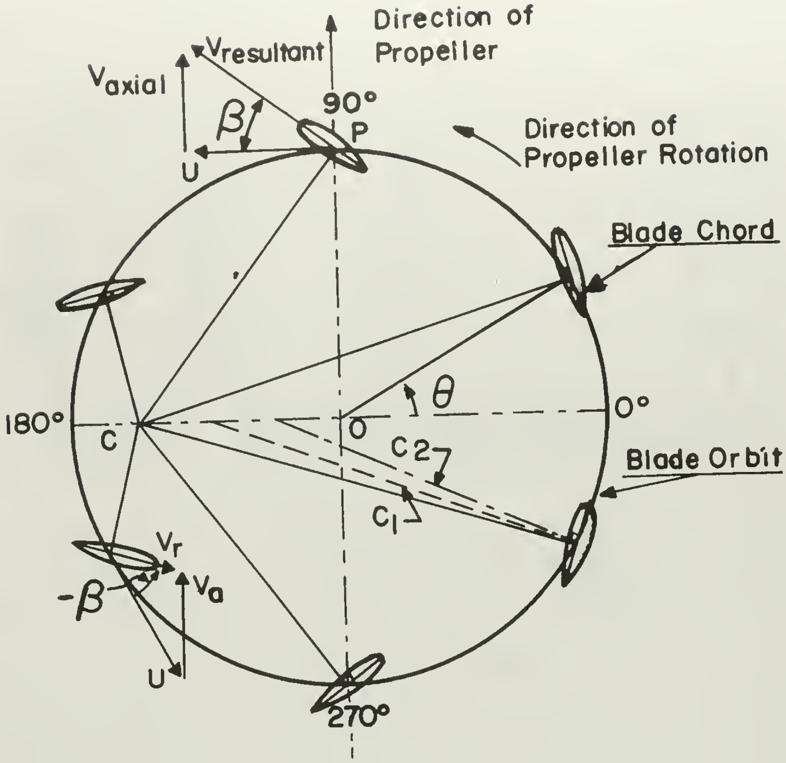


FIGURE 28 EFFECT OF AIR-FLOW ON PERFORMANCE OF BASE-VENTED PROPELLER (REF. 33)



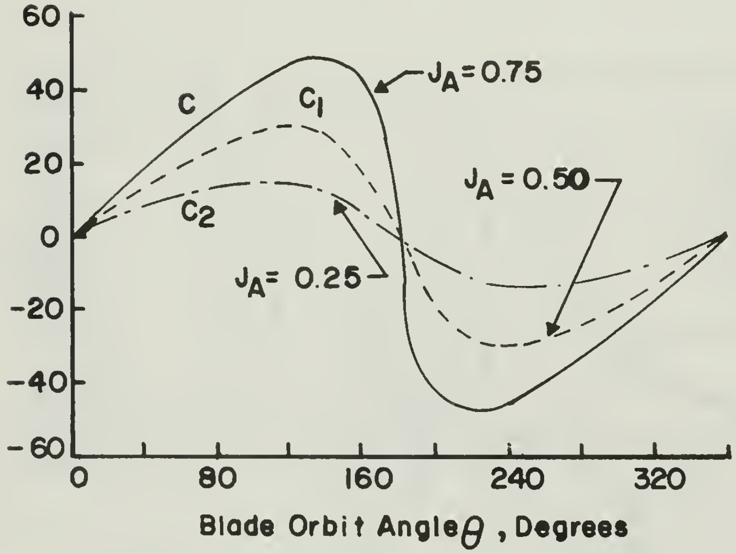


FIGURE 29 CYCLOIDAL BLADE MOTION AT VARIOUS ADVANCE COEFFICIENTS (REF. 198)

Investigations by Nakonechny[198] and Henry[196] have shown that the efficiency of the cycloidal propeller is quite low in relation to that of the conventional propeller. Henry concludes that the cycloidal propeller efficiency is in the range of 45 to 58 per cent while the screw propeller has an efficiency range of 66 to 76 per cent. Figure 30 from the report by Nakonechny shows the typical performance of a cycloidal propeller, whereas Figure 31 compares the efficiency of the cycloidal and conventional screw propellers.

3.6 PSUEDO-BLADE PROPULSORS

Among the more unique marine propulsion systems presently under investigation is a device called the psuedo-blade propulsor. The basic concept for this mechanism was originally stated by Foa in 1952[11,175]. The psuedo-blade propulsor employs a high energy primary fluid, discharging it into a lower energy secondary fluid through nozzles mounted on the periphery of a free spinning rotor, thereby causing a rotation of the rotor. The primary fluid regions are bounded by helical-shaped surfaces which are formed by the nozzles as the rotor revolves. Although the particles of primary fluid do not follow the same motion as the nozzles, they rotate about the same axis as the rotor with the identical angular velocity, thus constituting interfaces which separate the primary fluid from the secondary fluid. These interfaces are idealized into representing the formation of "psuedo-blades", so-called since their action is essentially identical to the flow induction process of real, solid blades.

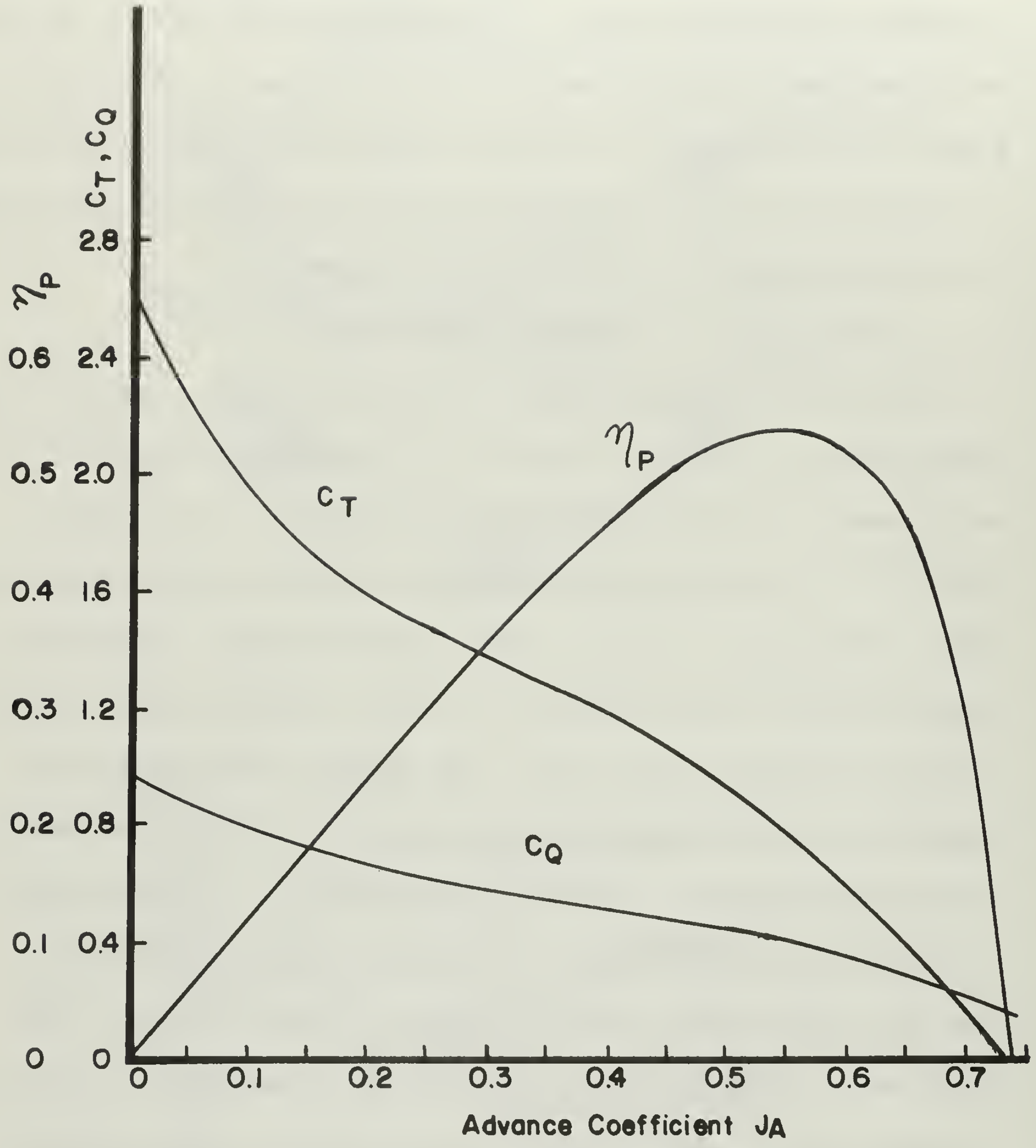


FIGURE 30 TYPICAL PERFORMANCE CURVES FOR VERTICAL AXIS (CYCLOIDAL) PROPELLERS (REF. 33)

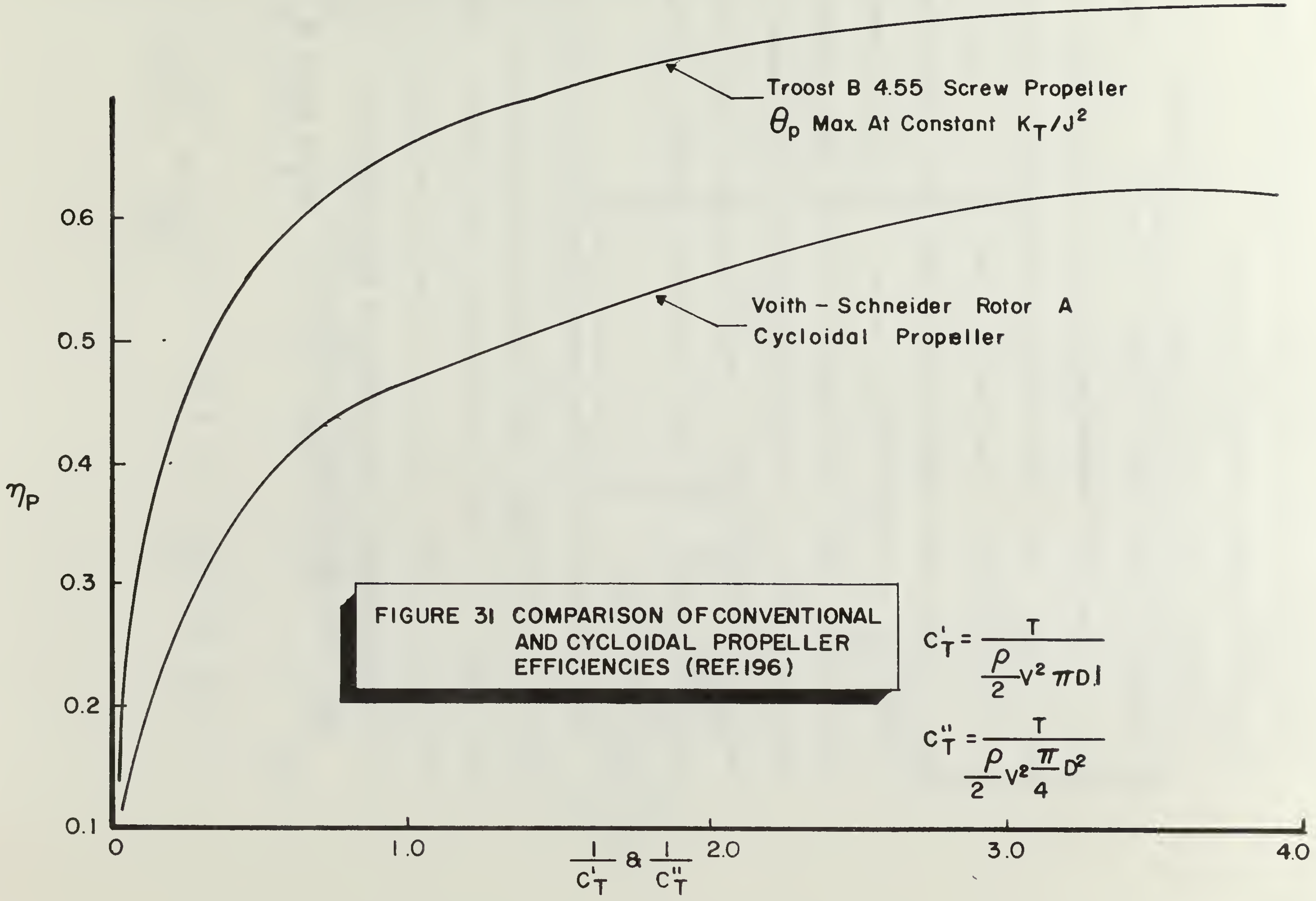


FIGURE 31 COMPARISON OF CONVENTIONAL AND CYCLOIDAL PROPELLER EFFICIENCIES (REF. 196)

The most interesting aspect of this system is the possibility of transferring energy and producing thrust utilizing the simplicity of direct ejection while at the same time theoretically eliminating the highly dissipative mixing of an ejector.

In order to understand the operation of this device, it is best to consider a plenum chamber as shown in Figure 32. It is assumed that this chamber is filled with an inviscid, incompressible fluid under pressure. The fluid is ejected from two nozzles of the same area with a velocity V. Thus the mass flows of the two jets are equal and their total energies, with respect to the plenum chamber, are the same. Since two flows are assumed to interact as shown with no losses, their total energy and velocity remain constant after they merge. Now, assume that the entire plenum chamber is moving in the y-direction at an absolute velocity V equal to the jet exit velocities. See Figure 33a for the velocity vector diagram before interaction.

In the absolute frame, the primary fluid energy is given by the sum of the static pressure and the velocity head, while the secondary fluid energy is only the static pressure. In the frame of reference moving with the plenum chamber, the velocities and energies of the two jets are identical, both before and after interaction; i.e.,

$$p_{t_1} = p_{t_2} = p_s + \frac{1}{2}\rho V_1^{\,2} = p_s + \frac{1}{2}\rho V_2^{\,2},$$

since

$$V_1 = V_2 = V = V_{1e} = V_{2e}.$$

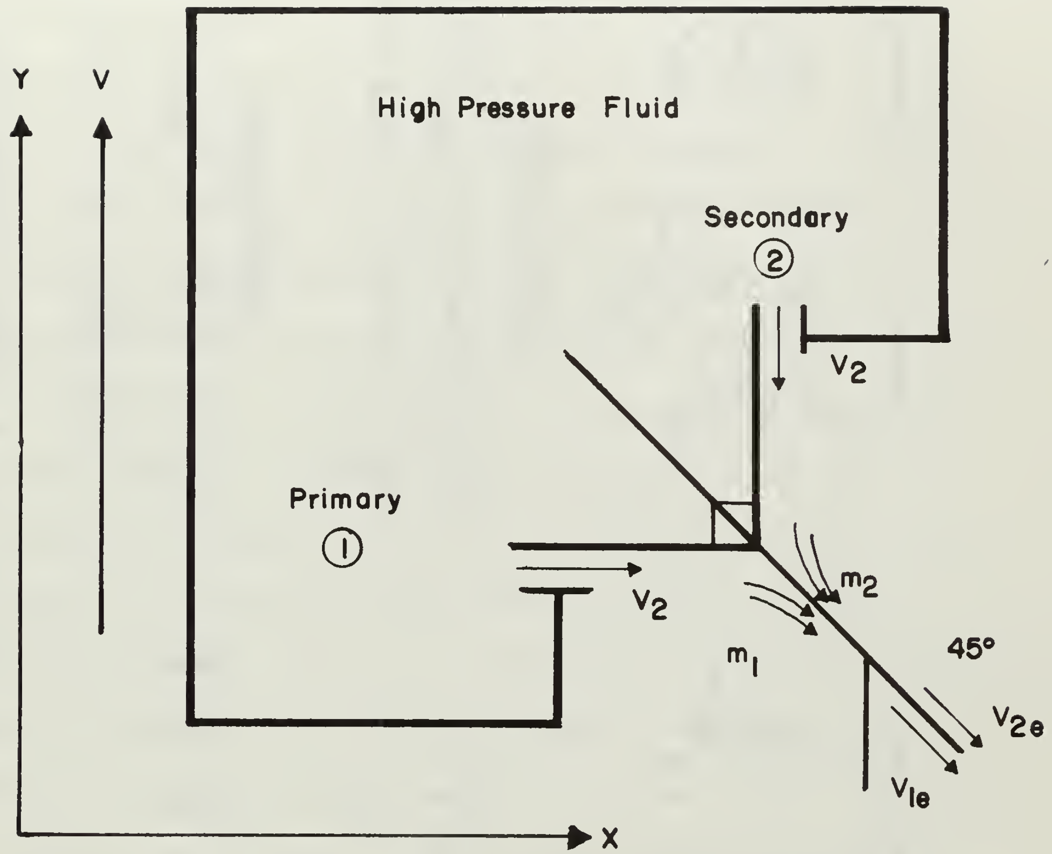
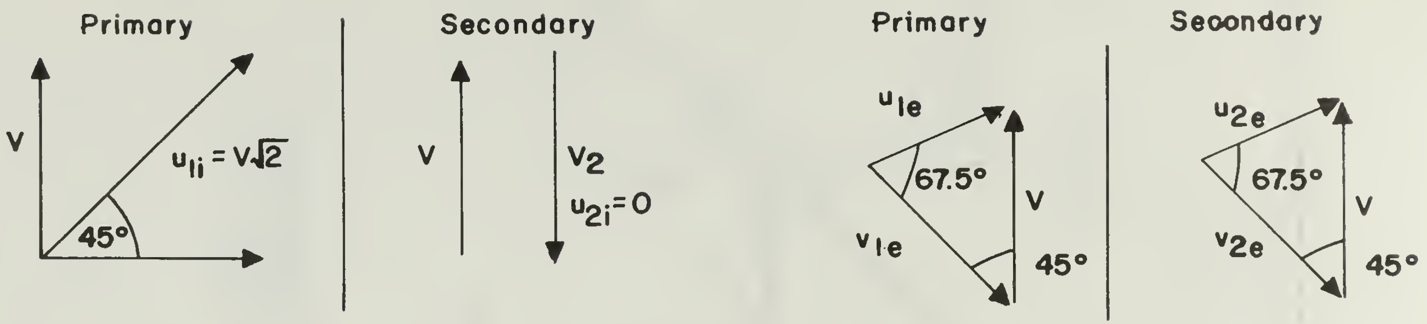


FIGURE 32 TWO FLUID JETS FROM MOVING PLENUM CHAMBER (REF. 174)



<u>Absolute Frame</u>

$$P_{T\dot{m}1} = P_s + \frac{\rho}{2} u_{1i}^2 = P_s + \rho V^2 \qquad P_{T\dot{m}2} = P_s + 0 = P_s$$

<u>Relative Frame</u>

$$P_{T\dot{m}1} = P_s + \frac{\rho}{2} V_1^2 \qquad P_{T\dot{m}2} = P_s + \frac{\rho}{2} V_2^2$$

a. BEFORE INTERACTION

<u>Absolute Frame</u>

$$P_{T\dot{m}1} = P_s + 0.293 \rho V^2 \qquad P_{T\dot{m}2} = P_s + 0.283 \rho V^2$$

$$P_{T\dot{m}1} = -0.707 \rho V^2 \qquad P_{T\dot{m}2} = +0.293 \rho V^2$$

<u>Relative Frame</u>

$$P_{T\dot{m}1} = P_s + \frac{\rho}{2} V_{1e}^2 = P_s + \frac{\rho}{2} V_1^2 \qquad P_{T\dot{m}2} = P_s + \frac{\rho}{2} V_{2e}^2 = P + \frac{\rho}{2} V_2^2$$

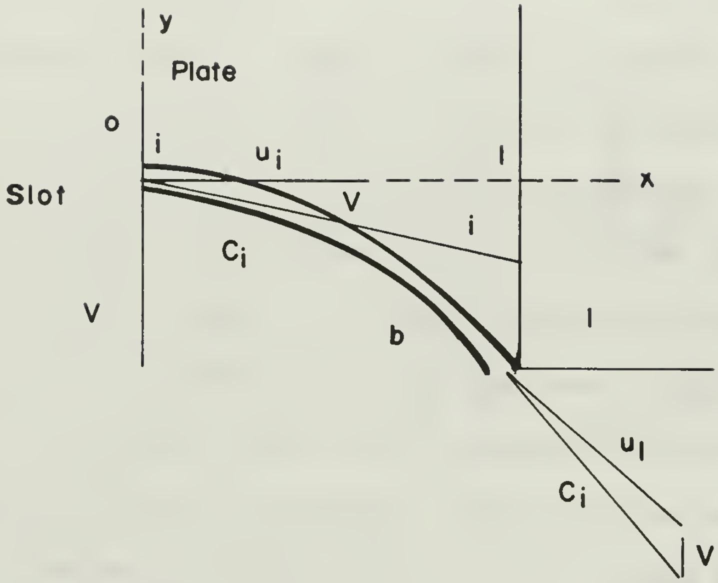
b. AFTER INTERACTION

FIGURE 33 (a) AND (b) VELOCITY VECTOR DIAGRAM (REF. 174)

Figure 33b shows the velocity vector diagram following the merging of the two streams, and it is seen that the fluids have a common direction and equal velocities in both the absolute and relative frames. As a result, it is evident that mechanical energy was transferred between flows since their total energies in the absolute frame are now the same. The decrease in energy of the primary fluid is $0.707 \rho V^2$ whereas the gain in energy by the secondary fluid is $0.293 \rho V^2$. This transfer of energy is the result of nondissipative collision of the particles in the flows and forms the basis for the psuedo-blade propulsion concept.

Note that the secondary fluid has no initial velocity in the absolute frame and, therefore, could be replaced in theory by a corresponding column of ambient fluid. This possibility is shown in Figure 34 in which the plenum chamber is replaced by a thin infinite plate with a slot in it. The chamber is assumed to be moving in the y-direction with a velocity V. An incompressible fluid under high pressure is assumed to flow out of the slot from the left side of the plate with an absolute velocity u_i into the incompressible medium present at a lower pressure on the right side of the plate. G. Avellone, et al.[174], show that the change in absolute energy along a representative streamline of this flow, with respect to reservoir conditions is

$$H_o - H = \rho C_i V(\sin\beta - \sin\beta_i). \quad (41)$$



$$H\,(\text{Relative}) = P_{sl} + \frac{\rho_l}{2} C_i^2$$

$$H\,(\text{Absolute}) = P_{sl} + \frac{\rho_l}{2} (C_i^2 + V^2 - 2C_i V \sin\beta)$$

$$dH = - \rho_l C_i V \cos\beta \, d\beta$$

$$H_0 - H_l = \rho_l C_i V (\sin\beta_l - \sin\beta_l)$$

FIGURE 34 PSUEDO-BLADE ANALOGY OF JET FROM MOVING THIN PLATE (REF. 174)

Equation (41) indicates that there is an energy change of the primary fluid in the absolute frame and this is a function of the change in the angle β. The primary fluid is deflected by an amount equal to the change in β when imparting a change in momentum to the secondary fluid. As a result of the original assumption of thinness for the plate, it cannot exert a force on the flow, and, thus, there must be a direct transfer of energy from one fluid to the other.

It is easy to proceed from this analogy of a thin infinite plate with a fluid flowing through a slot to the free spinning rotor of finite radius with several slots, or nozzles, located on the periphery. See Figure 35.

In recent years, Avellone and Sarro[177] have performed theoretical and experimental analyses of the psuedo-blade propulsor using various fluid mediums; e.g., steam as the primary fluid (gas at the rotor nozzle exit) and water as the secondary fluid. In their tests, they have fitted the device with a shroud which not only serves as a thrust augmenter, but also confines the energy exchange region so that the secondary fluid can undergo a compression,which would permit a "staging" process for the entire system.

In determining the overall performance of the psuedo-blade device, several definitions must be established. The total propulsor thrust is the sum of the shroud force and the rotor thrust. Two thrust augmentation ratios are defined: The first α_1, is the ratio of the thrust obtained with the rotor rotating to the thrust obtained with the rotor stationary; the second augmentation ratio α_2, is

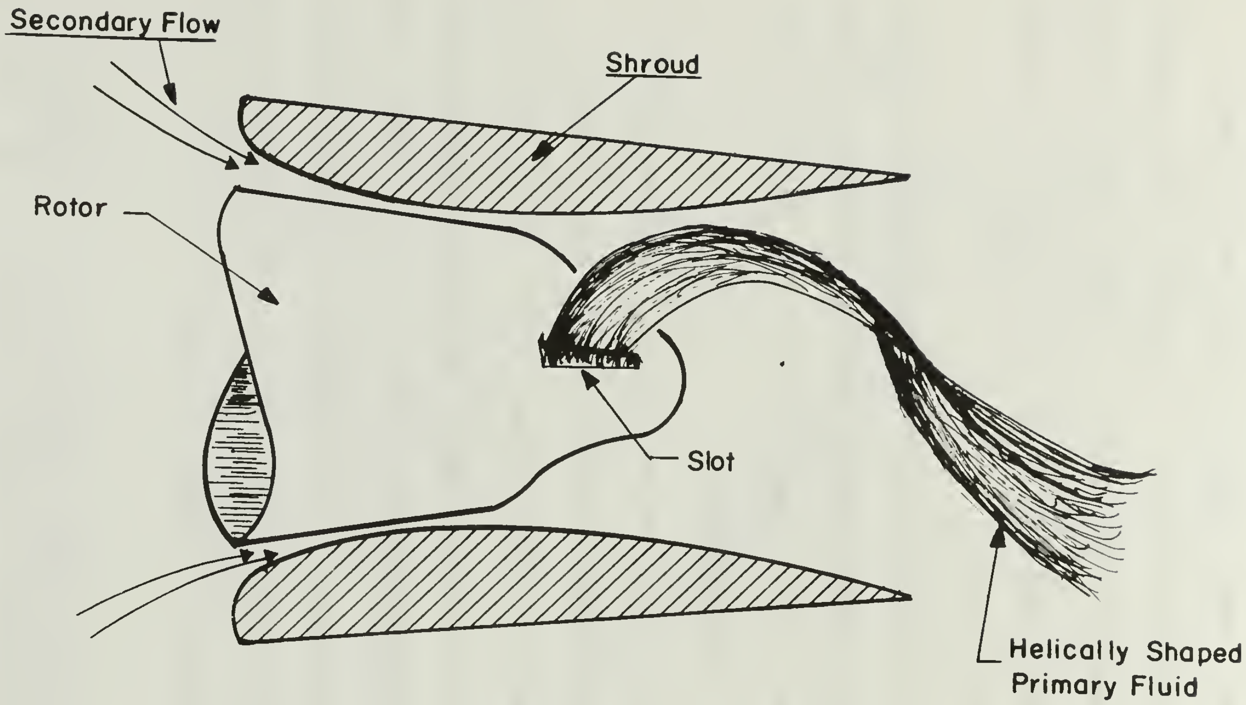


FIGURE 35 SCHEMATIC OF FLOW THROUGH PSUEDO-BLADE PROPULSOR (REF.177)

the measured thrust divided by the thrust of the rotor without a shroud. Therefore, it is seen that α_1 compares the thrust obtained under normal operating conditions to that of a pure reaction jet of the same area, while α_2 primarily demonstrates the advantage of a shroud. Typical augmentation ratios are shown in Figure 36.

The energy-transfer efficiency is defined as the ratio of the kinetic energy gained by the secondary fluid to that given up by the primary fluid and is given by:

$$\eta_{ET} = \frac{\dot{m}_s\left(V_s^2 - V_{s\infty}^2\right)}{\dot{m}_p\left(V_p'^2 - V_p^2\right)},$$

where V_s = secondary fluid velocity, $V_{s\infty}$ = vehicle velocity, V_p' = spouting velocity of primary fluid at the nozzle and V_p = primary fluid velocity at shroud exit. This efficiency is determined in an indirect manner and depends on a knowledge of the total pressure of the secondary fluid as well as the static pressures across the annulus or passage between the rotor and the shroud. Inasmuch as these pressures are not obtainable to any degree of accuracy, due to fluctuations throughout this passage, the energy-transfer efficiency is only a qualitative indicator of the performance of the psuedo-blade propulsor. A further consideration in the determination of this efficiency is the fact that the amount of energy actually transferred between the fluids is small, and, thus, a large error could result.

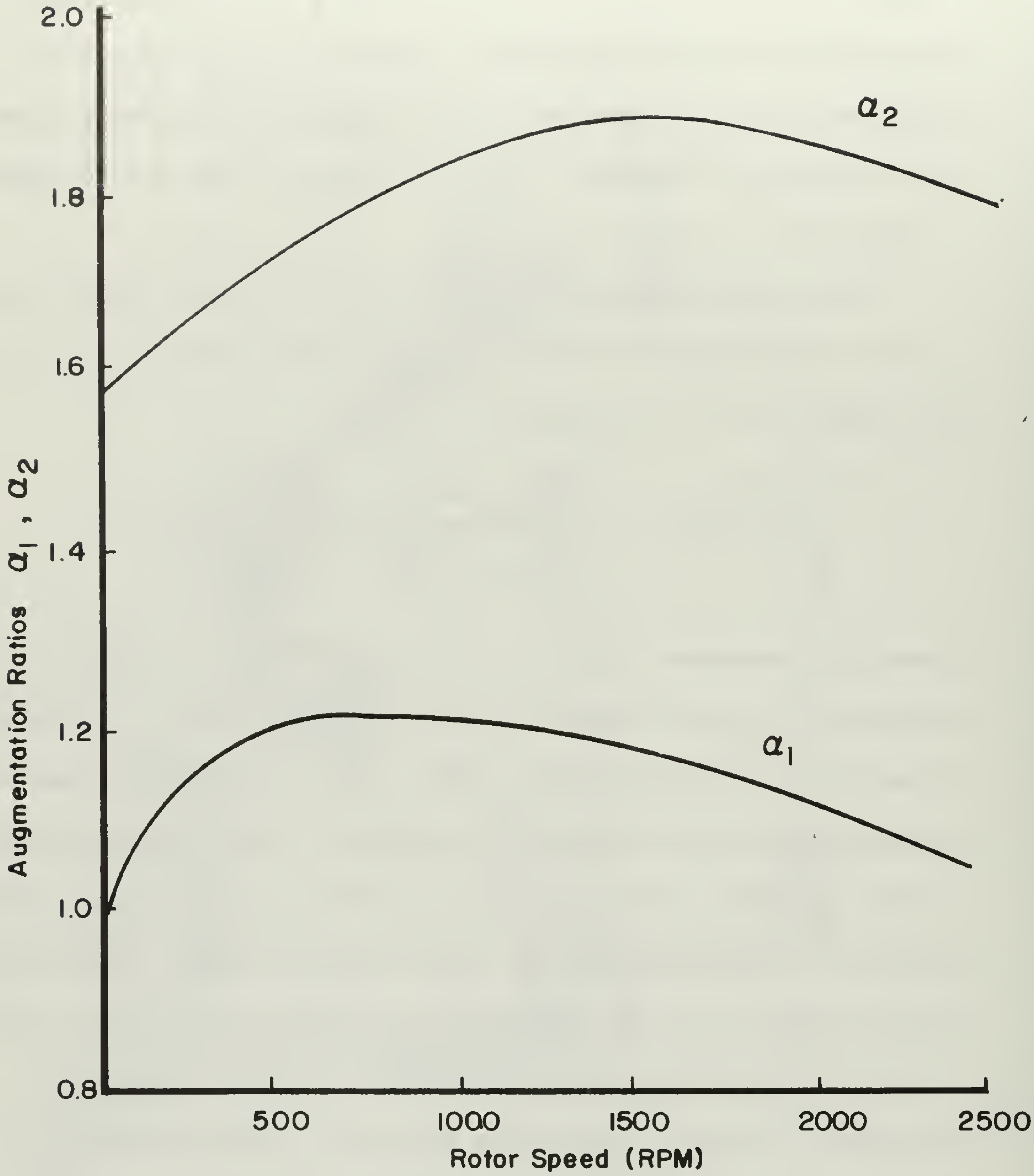


FIGURE 36 TYPICAL VALUE OF PSUEDO-BLADE PROPULSOR AUGMENTATION RATIOS vs. ROTOR SPEED (REF.174)

The final performance parameter considered is the propulsive efficiency, which, as before, is the ratio of the power output to the power input. The output power is the product of the total thrust of the device and the free stream velocity whereas the input power is the sum of the residual jet kinetic energy plus the kinetic energy based on the vehicle velocity existing at the rotor nozzle exit. This efficiency is given by

$$\eta_P = \frac{T_t \, V_{s\infty}}{\frac{1}{2} \dot{m}_p \left(V_p'^2 + V_{s\infty}^2 \right)} . \tag{42}$$

Figure 37 compared the typical efficiency of the psuedo-blade propulsor with that of a rocket motor versus the vehicle velocity. As shown on this diagram, the efficiency of the psuedo-blade device approaches 70 per cent whereas that of a comparable rocket motor is about 40 per cent at the same forward velocity.

As a result of the tests conducted on the experimental steam-water propulsor, it was found that the angle between the primary and secondary flows at the zone of the interaction varied from 30 to 45 degrees. This large angle of attack causes a large deflection of the primary fluid in the tangential direction and reduces the effective interaction flow area, causing the augmentation ratio to peak rapidly and drop off as rotative speed increases. This implies that the "psuedo-blades" are not penetrating deeply, and further design improvements such as "staging" will be required to make the blades more efficient at lower rotor speeds.

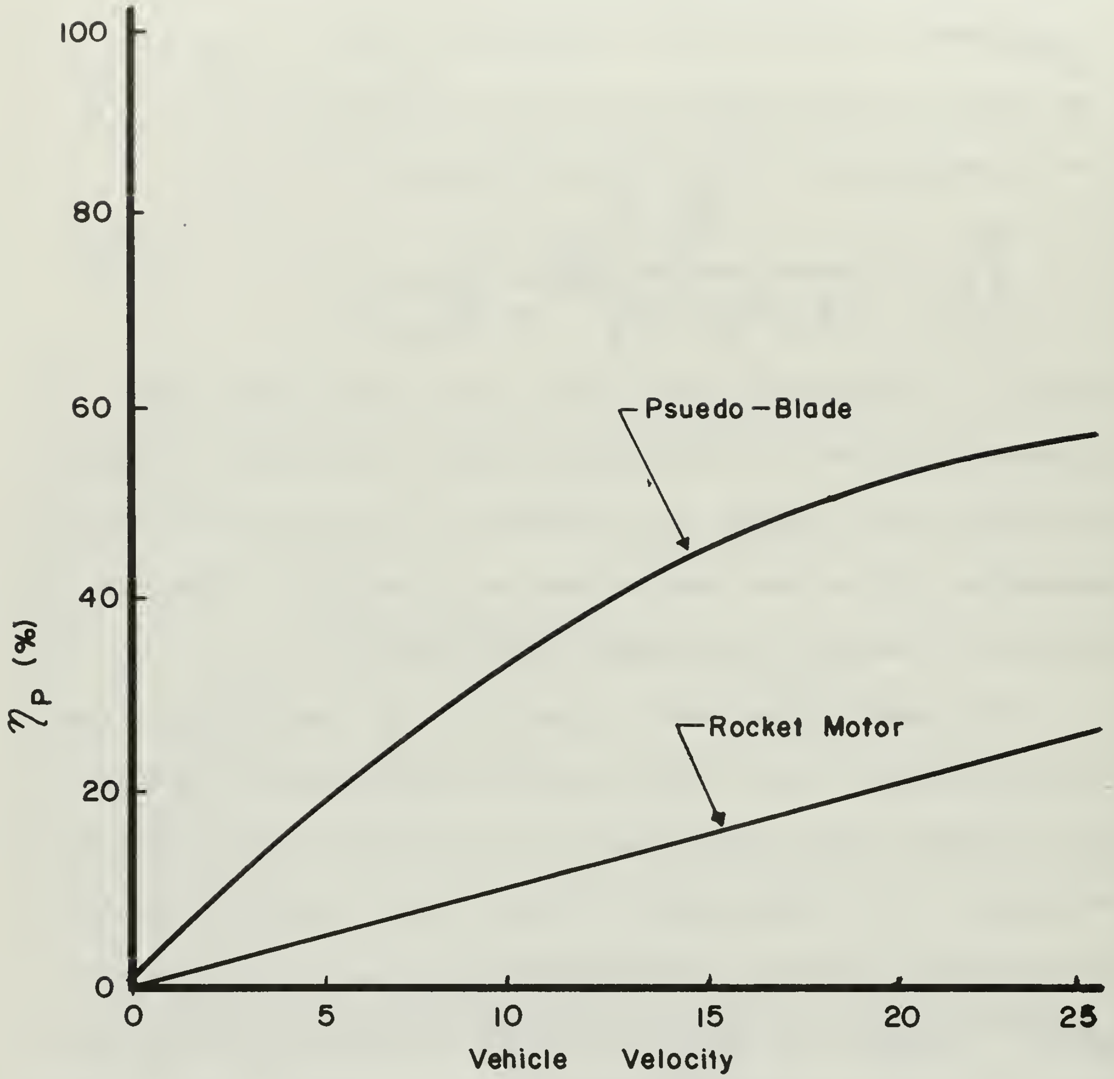


FIGURE 37 COMPARISON OF PSUEDO-BLADE EFFICIENCY AND ROCKET MOTOR EFFICIENCY (REF. 174)

3.7 SWIMMING (UNDULATING) PLATE PROPULSORS

The relatively high speed at which various species of fish (such as the porpoise) and aquatic mammals (such as the whale) have been observed to travel underwater has given rise to many theories attempting to explain this phenomenon. It is believed by some investigators that the capability of these animals to reduce the frictional resistance of their body surface by various means is the primary reason for their efficient propulsion. A consideration of the shape of many varieties of fish would indicate a minimum resistance due to form drag. Their bodies are of a slender cylindrical shape or resemble a planar form, having a finite length and width, but very little thickness.

Wu[74], in his paper on waving plates presents the following list of possible explanations:

(1) The ability of fish to maintain a laminar boundary layer at Reynolds numbers that would produce turbulent flow or separation around a rigid body.

(2) Their ability to convert a large portion of the energy input into propulsive power so that very little energy loss is created in their vortex wake.

(3) A built-in navigation system which enables them to follow the low-velocity water routes.

(4) An ability to extract energy from the eddies in a flow.

Regardless of the exact mechanism or inherent sensing device possessed by fish, their extraordinary swimming performance has inspired many investigations and studies designed to analyze their propulsive powers. Inasmuch as fish have flexible bodies which permit them to perform undulating motions while swimming, two-dimensional potential flow over a waving plate has been employed as a simple model in several theoretical approaches to the question. The motion of the body is treated as a progressing wave of given length and phase velocity. As the wave travels to the rear, the amplitude is increasing as a function of the distance from the leading edge and the phase velocity is greater than the free-stream velocity.

Gray and his co-workers[135] have shown from laboratory tests that there is nothing in the nature of the shape or body covering (scales and mucus) of a fish which could give it, when "coasting", a lesser resistance than that of a rigid piece of wood. After a study of the theory of the method of propulsion adopted by most aquatic animals; that is, sinusoidal motion of the whole or part of the body, Gray conducted experiments with a flexible flag, hanging vertically in a small wind tunnel, which was caused to periodically oscillate. The propulsive force derived from various frequencies and amplitudes of oscillation against a constant tunnel speed was measured. The results show how the drag varied with the speed of the waves along the body, relative to the speed of the stream. The drag of a fish can be referred to in terms of these two speeds in the same way that the resistance of a screw propeller is a function of revolutions and speed of advance. As a result of his tests, Gray asserted that a steadily swimming fish transmits a wave of increasing amplitude back along its body at a speed greater than the forward speed of the fish, thereby resulting in a thrust force.

Considering the speed and relative length of marine animals, they are capable of propelling themselves through water at a Reynolds number of the order of 10^5 or higher; therefore, the inertia forces in the surrounding fluid are an important factor in producing the propulsion. The viscosity of the water, in addition to causing the drag, is important in that it creates circulation around the body, thereby directly effecting the required thrust.

Wu,in his original analysis of the swimming plate, realized the complicated effects of the true fluid flow, and in order to simplify the discussion, limited himself to the case of two-dimensional potential flow. The following assumptions are made in his analysis:

(1) The waving plate is two-dimensional with negligible thickness.

(2) The fluid is incompressible and inviscid; however, the Kutta condition is imposed at the trailing edge.

(3) The forward motion of the plate is constant.

In the two-dimensional flow analysis offered by Wu, the hydrodynamic pressures are determined as a result of the harmonic wave motion which travels along the flexible body with increasing amplitude and a phase velocity greater than the forward velocity of the plate. The wavelength is generally of the order of the body length and decreases toward the rear of the body. An important parameter is the <u>reduced frequency</u> defined as

$$k = \frac{\omega c}{2 V_\infty},$$

where c = chord and $\omega = 2\pi n$ rad/sec = frequency of excitation. The product of the frequency f and wavelength L is the phase velocity V which must be in excess of the freestream velocity for generation of thrust. The pressure distributions can be integrated over the chord to determine the total thrust, power input and propulsive efficiency.

The preceding discussion of the theoretical analysis offered by Wu is considered sufficient for the purposes of this treatise. The reader is referred to the papers of Wu for his complete analysis.

A recent endeavor to investigate the effectiveness of undulating plates as a marine propulsion device has resulted in the physical application of these theories to a piece of machinery. Although the immediate results of the tests were not overly impressive, they indicated that with further design efforts and more extensive experimentation a useful system may be developed. M. Botman[133] has conducted a series of tests with a vehicle using an undulating plate of small aspect ratio as a propelling device. See sketch of device in Figure 38. A catamaran-type water vehicle was constructed and the plate was mounted horizontally in the centerline about two feet below the surface. The plate was hinged near the leading edge and received its oscillating motion from an eccentric mechanism which was driven hydraulically.

Speed measurements were made with a stopwatch over a fixed course, and after calculating the towing force required to pull the craft at a certain speed without the propulsor operating, the following average relationship between thrust and velocity was obtained:

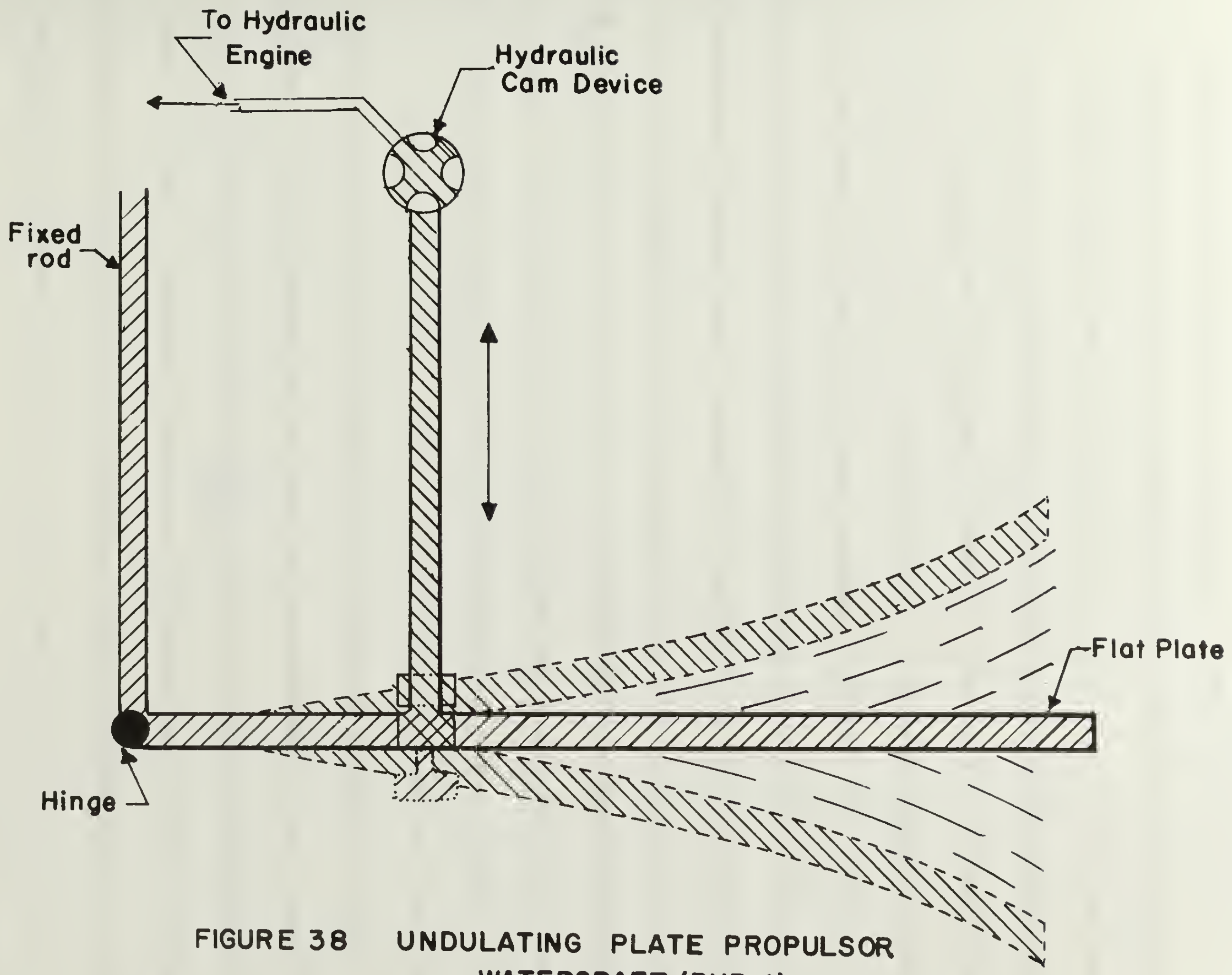


FIGURE 38 UNDULATING PLATE PROPULSOR WATERCRAFT (PUP-1)

$$T = 1.65\, V_\infty^2 .$$

This relationship was considered accurate only to within 10 per cent. From his measurements of frequency and hydraulic pressure, the power input to the plate was determined. The propulsive power was given by the speed-drag curve and resulted in propulsive efficiency defined as the ratio of propulsive power to input power.

Using ten different plates, with a variety of characteristic dimensions, Botman obtained very preliminary results which reflected the apparatus and methods used. However, some general relationships were obtained and the significance of reduced frequency as a correlating parameter was indicated. The propulsive efficiency, $\eta_p = \frac{TV_\infty}{P}$, where P represents total input power, was extremely low, but it was felt that this was a reflection of the excessively large power input that was available rather than the true worth of the device.

In an attempt to achieve self-locomotion by a swimming hinged hydrofoil and, simultaneously, offer experimental evidence concerning the propulsion produced by oscillatory motion of completely rigid surfaces, Kelly and Bowlus[139] conducted a series of tests at NOTS. They also intended to prove empirically the theory of Wu concerning his self-propulsion of semi-rigid or flexible bodies in a flowing stream of water.

The equations for the swimming plate as theoretically described by Wu, have been considerably simplified and solved on a computer by Kelly and Bowlus. In general, the results of this simplification still show good agreement with the theory of Wu. As in the report by Botman, the reduced frequency is of great significance and is used as a parameter for showing the drag (or thrust) variations as well as the theoretical propulsive efficiency of the hydrofoil. Figure 39 shows that the results of this series of tests conform essentially to the Wu theory predictions.

It was concluded that the Wu theory can successfully predict the thrust of an oscillating hydrofoil, whether rigid or flexible, although the results at higher reduced frequencies are not as conclusive as those in the lower range. It was found that the efficiency of self-propulsion is quite low if a point near the leading edge is held fixed and the rest of the foil is oscillated.

Summarizing the performance characteristics of the swimming or waving plate propulsors, it can be seen from Figure 40 that the thrust increases rapidly with the reduced frequency. The theoretical propulsive efficiency, defined by Botman as

$$\eta_{I} = T V_{\infty} / P ,$$

is observed to first increase, then decrease with the reduced frequency k, reaching a maximum value of about 85 per cent for $n = \frac{\pi c}{L} = 3$, when $k = \frac{\omega c}{2 V_{\infty}} \cong 4$ (L = wavelength and c = chord). In his actual test runs, the results of which are shown in Figure 41, Botman only realized efficiencies on the order of 20 per cent.

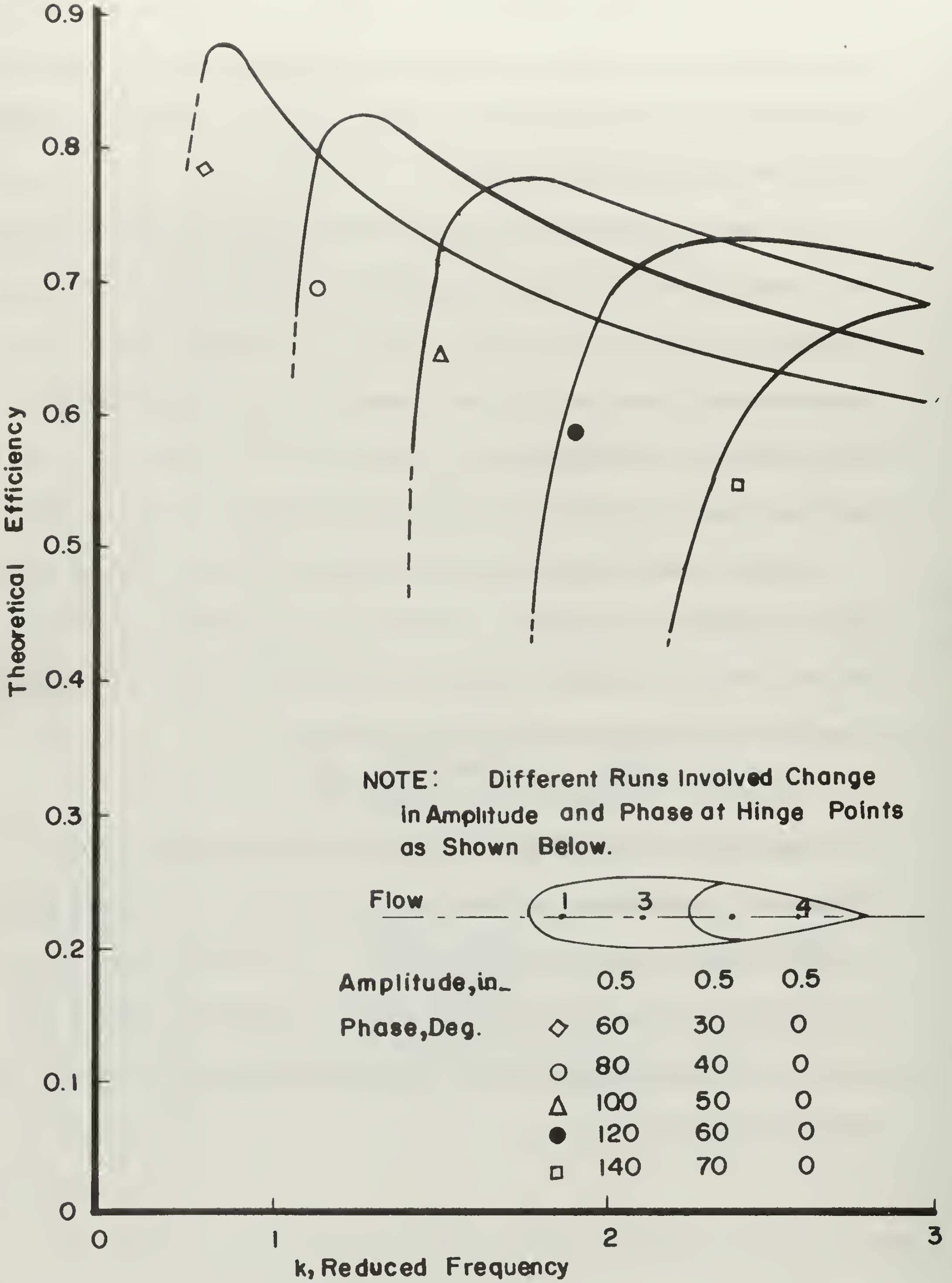


FIGURE 39 THEORETICAL EFFICIENCY FOR SINGLE-HINGED HYDROFOIL (REF. 139)

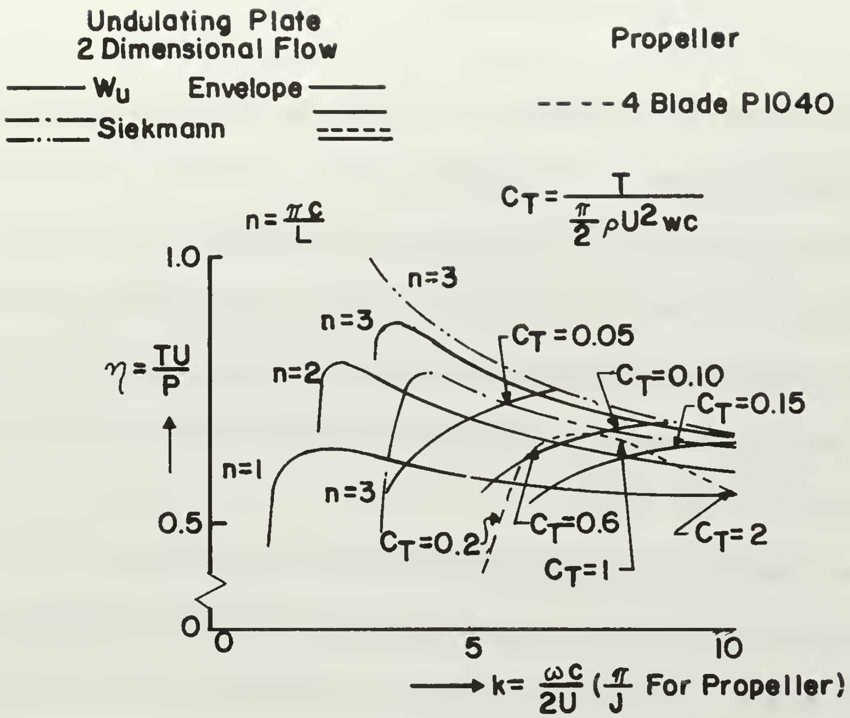


FIGURE 40 THEORETICAL PROPULSIVE EFFICIENCIES FOR UNDULATING PLATE PROPULSOR (REF.133)

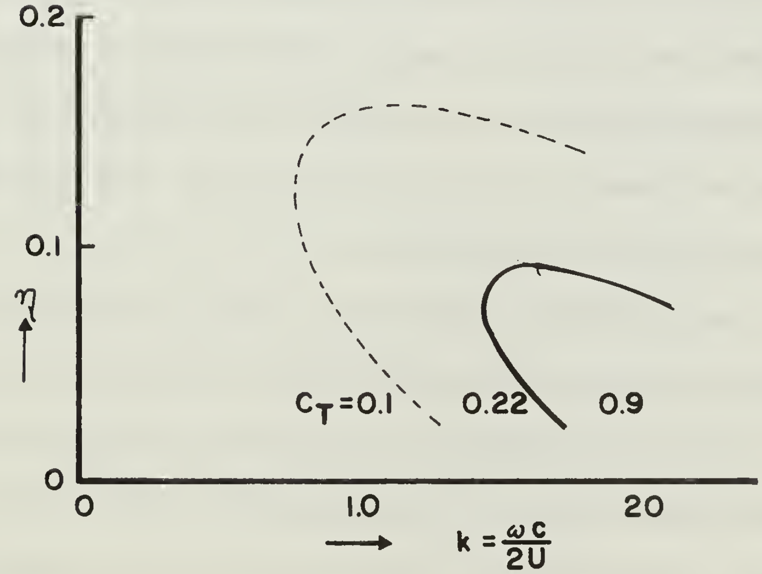


FIGURE 41 PROPULSIVE EFFICIENCIES (ACTUAL) FOR VARIOUS DIMENSIONS OF UNDULATING PLATES (REF. 133)

CHAPTER 4

ANALYSES OF INDIVIDUAL JET PROPULSORS

In the preceding chapter, rotating mechanisms were discussed in an order designed to show the natural evolution of the conventional screw propeller. The facts are, however, that the rotating device has very nearly reached its peak of performance and, to a greater extent, jet devices are being thought of as the marine propulsor of the future, particularly since these devices are more efficient at high speeds.

An identifying feature of these jet-type devices is the presence of a nozzle which actually constitutes the thrust producing element for the system. One of the systems considered in the preceding chapter was the psuedo-blade propulsor, and this rather unique thruster actually forms an excellent transition point from the indirect to the direct propulsors. It is capable of operating without a shroud, and the addition of the duct is assertedly for thrust augmentation purposes. However, the utility of such a device would be largely curtailed without the shroud to act as a constraint on the fluid flow. The psuedo-blade propulsor appears to meet the criteria of both categories and, thus, could be placed in either one.

The principal disadvantage of the jet propulsors is their high exhaust velocities which place them in a region of low efficiency. For simplicity of operation and potential speed, the jet thruster is far superior to the propeller device, but it will be necessary to develop means of greatly reducing the viscous resistance on a body travelling underwater before the jet propulsor can operate at a reasonably effective speed ratio. (See Figure 8 in Chapter 2.) Appendix A gives a summary of the most promising techniques under study for reducing the drag on a submerged body.

In the following sections, the principal jet-type propulsors, suitable for propelling a marine vehicle or weapons system, will be described and an analysis given in those cases where such a presentation will add to the value of this study. The analysis of the arbitrary propulsion system given in Chapter 2 will suffice as a general source of information concerning the development of thrust by a jet device.

4.1 DUCTED PROPELLERS

The use of shroud rings as a means of accelerating the velocity of the flow at a propeller in a manner similar in principle to the air-breathing fan engine has been known for many years. In fact, a patent for a screw propeller operating in a short tunnel was submitted in 1845 by B. Griffith. Another use of ducts in the water environment involves the pumpjet in which the shroud serves to decelerate the fluid flow at the propeller in order to delay the inception of cavitation. The pumpjet will be discussed in detail in a later section.

The principal parts of the ducted device are a rotor or propeller, a shroud in the form of a thin annular-shaped hydrofoil and stationary guide vanes. The shroud is best described as a Kort nozzle which is named after its inventor, L. Kort, a German engineer. This is a short nozzle which is stationary or rigidly attached to the body that the system is to propel. Figure 42b shows the action of the Kort nozzle or ducted propeller as compared to that of a conventional water

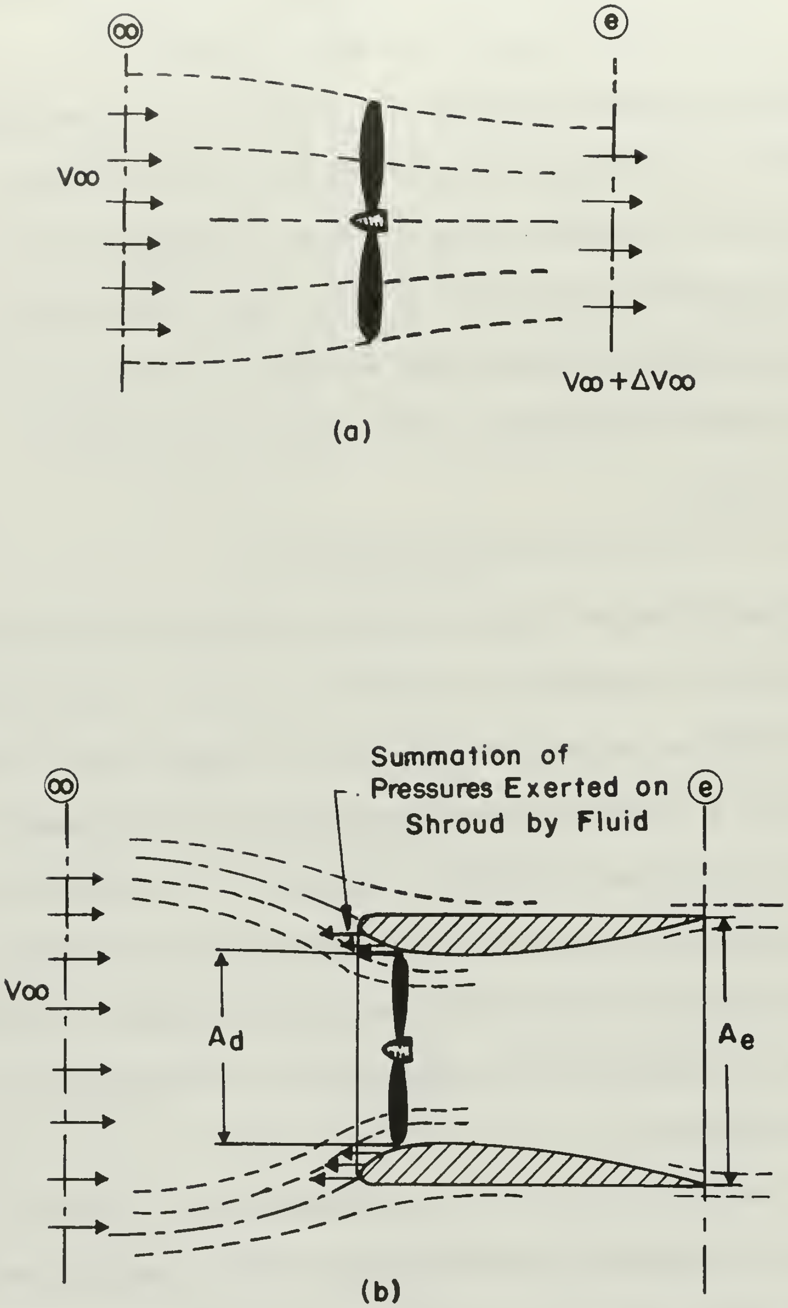


FIGURE 42 COMPARISON OF FLOW THROUGH (a) CONVENTIONAL SCREW AND (b) DUCTED PROPELLERS (REF. 11)

screw shown in Figure 42a. The flow is seen to contract after passage through the disk in the ordinary propeller as a result of continuity. The contraction is decreased in the nozzle so that for equal amounts of water passing through the propellers, the exit velocity ($V_\infty + \Delta V_\infty'$) behind the nozzle is less than the wake velocity ($V_\infty + \Delta V_\infty$) behind the open propeller. This results in an increase in the ideal propulsive efficiency of the shrouded propeller over the unshrouded propeller in the ratio of

$$(2V_\infty + \Delta V_\infty)/(2V_\infty + \Delta V_\infty').$$

The primary result attained by adding a duct to a propeller is the production of thrust on the duct, resulting from an increased flow rate through the propeller. The thrust forces exerted on the shroud as a result of pressures are shown in Figure 42b. Since the loading on the blades can be made lighter, cavitation inception and noise radiation can be decreased in intensity. A further benefit of the duct is the larger lift and thrust produced at a given angle of attack by the interaction between the duct and the propeller as compared to the lift and thrust developed by the separate elements. This feature makes it attractive for use in high speed hydro-planing vehicles.

In 1954, Lerbs presented an analysis of the flow and forces generated by a shrouded propeller[161]. He replaced the components by various vortex singularities and developed a mathematical model for which he was able to deduce the velocity fields and the net forces on the components of the system. Improvements in the lifting-line theory and the three-dimensional vortex theory for conventional propellers have resulted in more accurate analyses of the ducted propeller. Investigators have combined these theories with models based on a linear ring-foil theory which includes the effect of camber, thickness and angle of attack of the axis of the device.

Morgan presents an analysis of the shrouded propeller in Reference 33. The following assumptions are made concerning the fluid flow field and the device itself:

(1) The ducted system consists of an annular hydrofoil of finite length with an internally operating propeller having a finite number of blades; the annular foil is, in general, axisymmetric.

(2) It is assumed that the linearized lifting-line theory can be applied to the device; i.e., thickness and camber of the hydrofoil are small.

(3) The fluid is inviscid and incompressible, and no separation occurs on the duct.

(4) Body forces, such as gravity, are neglected.

(5) The free stream flow is axisymmetric and steady with respect to a coordinate system attached to the propeller.

(6) The linearized flow around the annular hydrofoil can be modeled by a distribution of ring vortices and ring sources along a cylinder of constant diameter.

(7) The trailing vortex system of the duct has the constant diameter of the duct and extends from the duct to infinity.

(8) The influence of all induced velocities on the shape of the trailing vortex system of the duct is neglected.

(9) The propeller flow field can be represented by a lifting line and helicoidal trailing vortices where each trailing vortex line lies on a cylinder of constant diameter and is of constant pitch.

As in the previous discussion of the conventional propeller, the method of singularities is used to obtain a solution by summing the velocities induced by individual singularities, ring vortices and sources for the annular hydrofoil. The mathematical model will be a distribution of ring vortices and sources lying on a cylinder of a diameter corresponding to that of the duct and of length equal to the chord of the duct.

The annular hydrofoil section is assumed known; the boundary conditions which must be satisfied on the foil are: (1) On the surface, the normal velocity must be zero. (2) At the trailing edge, the Kutta condition is satisfied. Using these boundary conditions, the strength of the ring vortex and source distributions are determined. If a propeller is in the duct or the duct is at an angle of attack, the ring vortex strength is dependent on the angular position around the duct and a trailing vortex system exists behind the duct. The induced velocities of this system must be superimposed on those of the vortices and ring sources. (Since governing equations are linear in terms of a velocity potential, these velocities may be added.) The required mathematics is quite involved, and it will be sufficient for our purposes to state the results. One can conclude that the source-sink strength is a function of the thickness slope only. This implies for the axisymmetric duct that, within the limitations of the linearized theory, the source strength and the ring vortex strength are independent of angle. The ring vortex strength is a function of both thickness and camber, as well as the radial velocities of any other singularities in the flow.

The velocity field of the ducted propeller is found by summing the free-stream velocity, the velocity induced by the duct including the trailing vortex system, and the velocity induced by the propeller. The velocities induced by the duct at the propeller depend partly on the propeller circulation, while the velocities induced by the propeller at the duct depend partly on the duct circulation. Thus an iterative program is required to solve this complicated problem.

For those interested in designing a propeller-duct combination, the analysis discussed above is of great value, but for a basic understanding of the performance characteristics of this propulsor, the formulation by Foa will be used[11]. Referring again to Figure 42b and assuming that the flow is not choked at the throat and there is no separation, the cross-sectional area of the nozzle exit, A_e, is the governing factor for the mass flow through the duct, vice A_d, the area of the propeller disk. Assuming further that the exit pressure is equal to the ambient pressure, and the entropy change is negligibly small, we can state that the density at the exit differs only slightly from the free-stream density. Therefore, we can write for the ducted propeller:

$$\dot{m} = \rho_\infty A_e V_e$$

$$T = \rho_\infty A_e V_e (V_e - V_\infty)$$

$$\eta_o = \frac{1}{P} \rho A_e V_e V_\infty (V_e - V_\infty),$$

where P is the power input to the shaft.

$$\eta_P = \frac{2 V_\infty}{V_e + V_\infty}.$$

The thermal or cycle efficiency, which was defined in eq. (18), becomes:

$$\eta_{th} = \frac{V_e^2 - V_\infty^2}{2P/\dot{m}}$$

or

$$\eta_{th} = \frac{1}{4} \eta_o \left[3.0 + \left(1 + \frac{4P\eta_o}{\rho_\infty A_e V_\infty^3} \right)^{1/2} \right].$$

Figure 43 compares the ideal propulsive efficiency of the ducted propeller to the conventional propeller. The relationship used is

$$\frac{(2-\eta_P)(1-\eta_P)}{\eta_P^3} = \frac{2}{\pi} \frac{C_P}{J_A^3} \frac{A_d}{A_e}. \qquad (43)$$

From this graph, it is seen that the ducted propeller has a higher ideal propulsive efficiency than the conventional propeller. This is a result of producing thrust with a greater mass flow rate and a lower exit velocity. The figure indicates that the efficiency of a ducted propeller can be as high as 80 per cent depending on the area ratio, A_d/A_e.

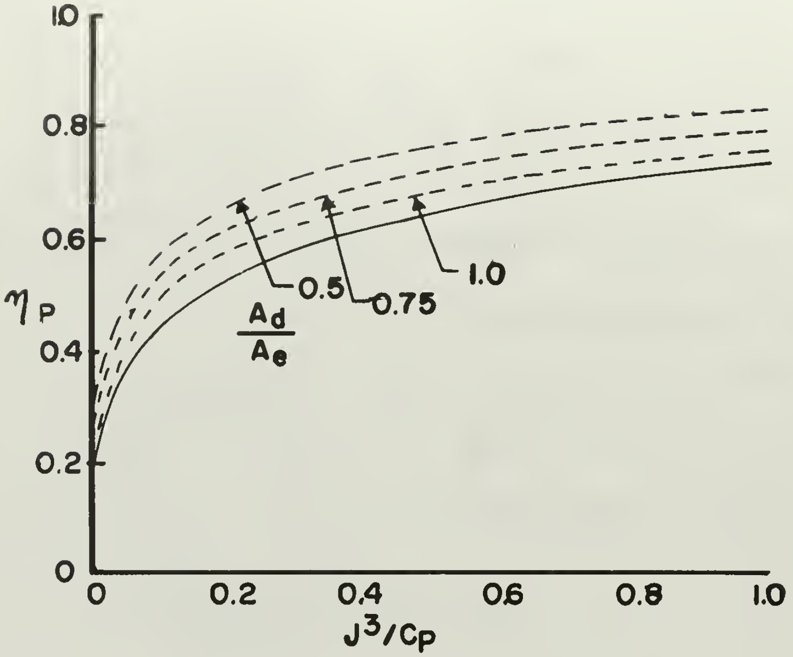


FIGURE 43 COMPARISON OF IDEAL PROPULSIVE EFFICIENCIES OF CONVENTIONAL AND DUCTED PROPELLERS (REF. 11)

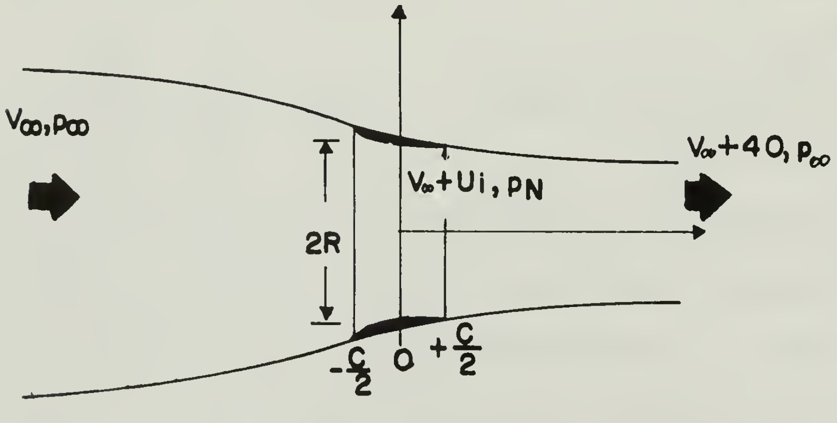


FIGURE 44 COORDINATE SYSTEM FOR SHROUDED SUPERCAVITATING PROPELLER (REF. 33)

The derivation of a thrust augmentation ratio as a result of ducting follows from Foa[11]. Consider the static thrust (when $V_\infty = 0$) for the unducted propeller:

$$\dot{m} = \frac{1}{2} \rho_\infty A_d V_e$$

$$\eta_{th} = \rho_\infty A_d V_e^3 / 4P \tag{44}$$

$$T_{static} = \frac{1}{2} \rho_\infty A_d V_e^2 = \frac{1}{2} \rho_\infty A_d \left[\frac{4 \eta_{th} P}{\rho_\infty A_d} \right]^{2/3}.$$

For the ducted propeller,

$$\dot{m} = \rho_\infty A_e V_e$$

$$\eta_{th} = \rho_\infty A_e V_e^3 / 2P \tag{45}$$

$$T_{static} = \rho_\infty V_e^2 A_e = \rho_\infty A_e \left[\frac{2 \eta_{th} P}{\rho_\infty A_e} \right]^{2/3}.$$

Comparing eqs. (44) and (45), we can see that the ducting increases the static thrust of the propeller, all conditions equal, by a factor of $(2\, A_e/A_d)^{1/3}$; i.e.,

α_3 = static thrust augmentation ratio

$$\alpha_3 = \frac{\text{static thrust of ducted propeller}}{\text{static thrust of unducted propeller}}$$

$$\alpha_3 = (2\, A_e/A_d)^{1/3}.$$

4.2 SHROUDED SUPERCAVITATING PROPELLERS

We have previously discussed the ducted subcavitating propeller and the theory that goes into the design of this type of propulsor. Since the supercavitating propeller offers the possibility for efficient propulsion at speeds desired for the operation of modern marine vehicles, it is only natural that this type of propeller should be combined with the accelerating or Kort nozzles. Since this method allows some control over the fluid flow through the propulsor, by predetermined design of the area ratio, it is possible to extend the vehicle forward speed range into the lower bracket, as we saw in the case of the ventilated propeller.

Figure 44 from Reference 33 shows a typical shrouded supercavitating propeller. A comparison of Figures 42 and 44 shows that for the supercavitating shroud, the leading edge is sharper and the foil section is much thinner.

By using the methods described in the section under supercavitating propellers, the total thrust developed by the nozzle and the propeller on the fluid is

$$T_{total} = \rho_\infty A_d \left(V_\infty + u \right) u_0 .$$

The thrust developed by the propeller alone is given by

$$T_{prop} = \rho_\infty A_d \left(V_\infty + \tfrac{1}{2} u \right) u_0 .$$

This is the same result as for a propeller acting in a free stream. The thrust produced by the nozzle alone is then the difference between these two expressions. The average velocity induced by the nozzle is the mean additional velocity induced by the nozzle-propeller combination at the disk less one-half the additional downstream velocity. Assuming that the effect of the nozzle is due to the ring vortices of constant radius R with vorticity distribution of strength $\gamma(x)$, for $-C/2 \leq x \leq C/2$, then

$$T_{nozzle} = 2\pi R \rho_\infty V_\infty \int_{-C/2}^{C/2} \gamma(x, R) \frac{V_r(x, R)}{V_\infty} dx,$$

where $V_r(x,R)$ = radial velocity induced by the propeller. (The vortex strength $\gamma(x)$ is positive when lift generated is toward the interior of the nozzle.) From linear theory, the vorticity distribution $\gamma(x)$ is the sum of: (1) the vorticity generated by the radial angle of attack due to the induced radial velocity of the propeller, $\gamma_v(x)$; (2) the vorticity due to camber, $\gamma_c(x)$; and (3) the apparent vorticity due to thickness of profile, $\gamma_t(x)$. The radial velocity induced by the propeller is a function of the total disk loading as well as the distribution of loading on the propeller. The propeller loading is assumed to be radially uniform. The thrust developed on the nozzle and the mean induced through flow velocity can be determined as well as the pressure reduction achieved by use of the nozzle. The calculation of performance parameters for the shrouded supercavitating propeller system is essentially a combination of the methods used for each of the devices separately. The above technique is essentially the same as that for the ducted subcavitating propeller.

It should be recalled that in calculating the performance of a ducted propeller, the external drag due to adding the shroud must be considered. Typical test results for the ducted propeller system are shown in Figure 45.

The ducted propeller was selected as the introductory device under this category of jet propulsors since it represents the low end of the power spectrum of a class of thrusters which are in general termed pumpjets or waterjets. The screw propeller enclosed in a shroud differs from the pumpjet in degree of compression and intensity of thrust provided; however, the basic operating principles are similar in both devices.

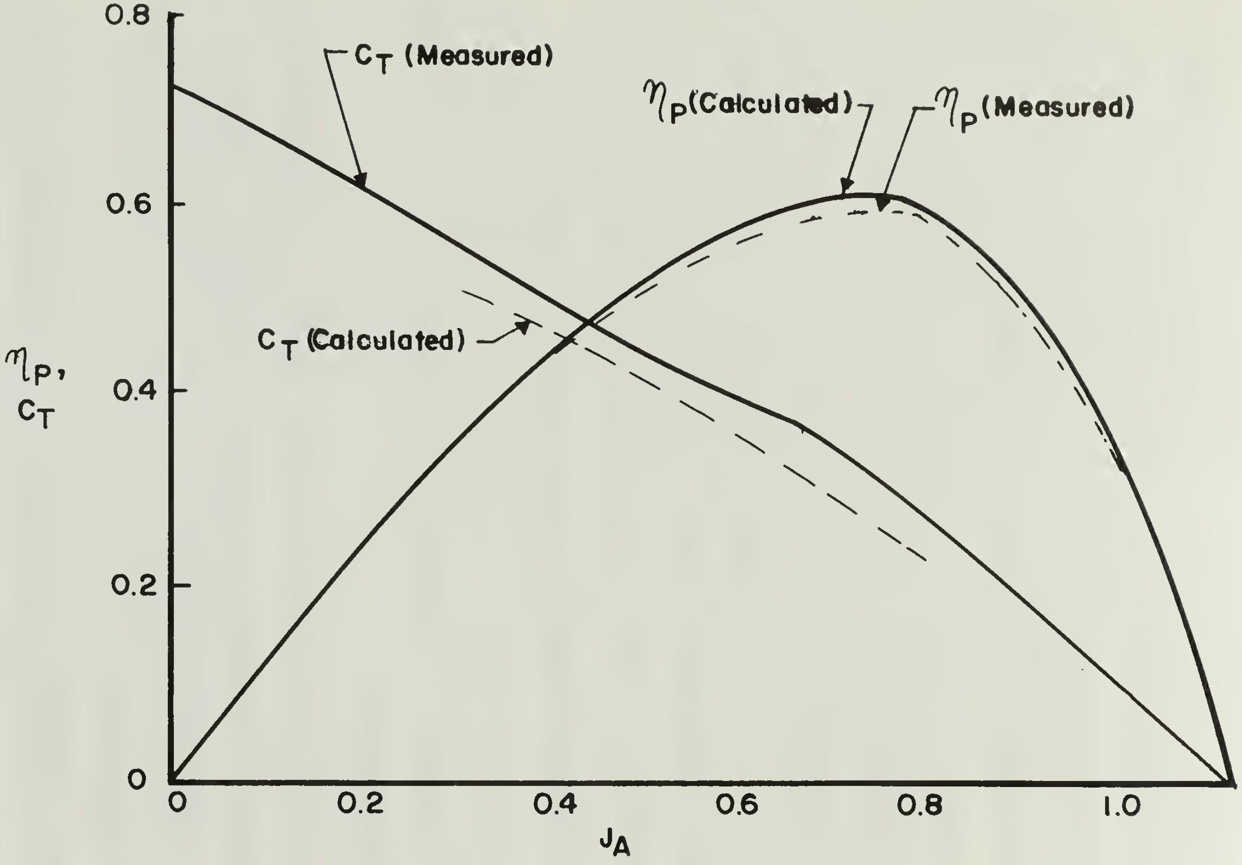


FIGURE 4 5 COMPARISON OF CALCULATED AND THEORETICAL CHARACTERISTICS OF SHROUDED SUPERCAVITATING PROPELLER SYSTEM (REF. 33)

4.3 WATERJETS (PUMPJETS)

Due to the current interest in obtaining high speed marine vehicles, the waterjet has recently become the object of intensified research efforts; however, according to Schuster, et al.[213], who provide a history of the waterjet, vessels were propelled by a jet device as early as 1661. Progress has been especially slow in this field due to its operation in a range where it is inherently inefficient. Recall that the ideal propulsive efficiency for a jet device is:

$$\eta_P = \frac{2\gamma}{1+\gamma} = \frac{2}{1 + 1/\gamma},$$

where $\gamma = V_\infty / V_e$. Thus, a higher propulsive efficiency can be obtained by keeping the exit velocity of the jet as close to the forward velocity of the craft as possible. Of course, in order to operate in this manner and still maintain a given thrust, means must be found to increase the mass flow rate through the device. This can result in a ducting system which is entirely too heavy and has an excessive amount of external drag. From this discussion, it is obvious that a number of factors must be considered in judging the performance capability of a particular propulsor.

Figure 46 depicts the general arrangement of a waterjet. The three basic elements of the device are: (1) an intake duct which picks up water from the surroundings, (2) a pump which transfers energy to the liquid medium, and (3) an exhaust nozzle fitted with stators which guide the fluid out in an axial direction. As with all propulsive devices, the resulting momentum exchange produces the desired thrust. The waterjet appears to be a ducted propeller, but with a much longer shroud, which necessitates a completely different analysis.

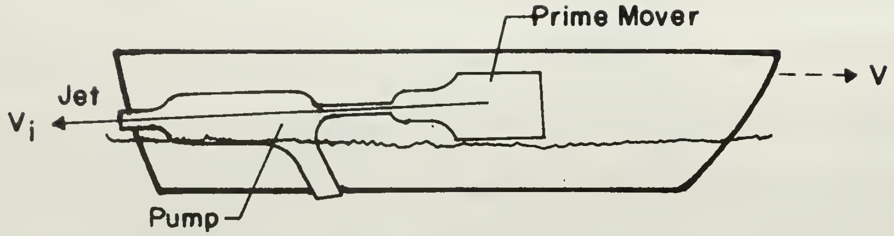


FIGURE 46 GENERAL ARRANGEMENT OF WATERJET INSTALLATION (REF. 114)

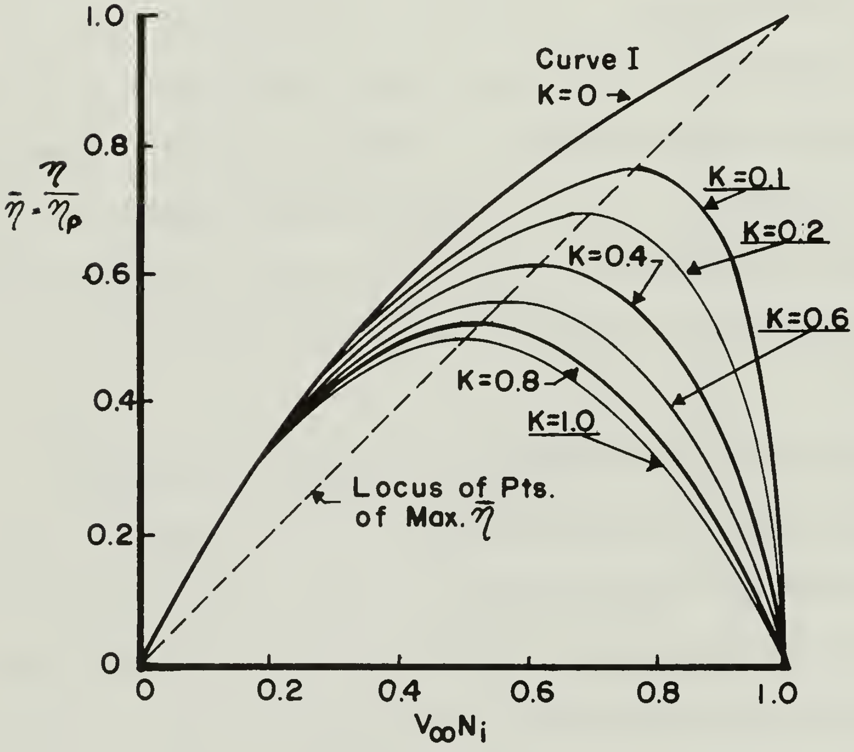


FIGURE 47 THEORETICAL EFFICIENCY FOR WATERJET SYSTEM AS CALCULATED BY CONTRACTOR (REF. 114)

The specific vehicle in which the waterjet is installed will, of course, have a great influence on the design and shape of the ducting used to suck the water into the machine. The losses will naturally be higher than those in the conventional propeller system, and due to the longer length of the duct, will exceed the losses encountered in the ducted propeller. For an optimal propulsive efficiency, a low jet velocity is desired; but to ensure an efficient overall system, the duct losses must be minimized. The possible deteriorating results of cavitation must be considered in designing the inlet. Although this aspect of the propulsor is not our prime concern, the significance of a proper inflow to the pump deserves mention. Brandau presents a detailed discussion of the various requirements for ducting in a waterjet system in Reference 112.

The most important component of the waterjet is the pumping mechanism which must maintain a high water through-flow rate while keeping the head rise low to optimize the propulsive efficiency. The function of the pump in the waterjet is the same as that of the propeller in the open or shrouded configuration; i.e., to accelerate the flow or increase the energy of the fluid, resulting in a thrust force.

Brandau includes three types of pumps in his discussion: (1) the centrifugal or radial flow pump which is capable of obtaining a high head rise, (2) the mixed flow pump which provides an intermediate level head increase, and (3) the axial flow pump or propeller which is favored due to its low head rise. The onset of cavitation, which is highly dependent on the rotative speed and local pressure of the pump, can be contained more easily with the axial flow pump as a result of this minimum pressure rise characteristic.

An important parameter in the evaluation of pumps is the "specific speed" which is defined as

$$N_s \equiv \frac{N\,Q^{1/2}}{H^{3/4}},$$

where N is the pump rotative speed in revolutions per minute, Q is the rate of flow or discharge in gallons per minute, and the total head H developed by the pump is given in feet of water. Specific speed is normally used in this form as a pure number although it is not dimensionless. Its significance arises from the fact that it provides a basis for determining the effectiveness of a given pump, through the comparison of the mass flow rate to the pressure rise at constant rotative speed, or a warning of the inception of cavitation by comparing rotative speed with the pressure increase. The normal ranges of specific speed for the three types of pumps are: (1) centrifugal pumps, $N_s < 4000$, (2) mixed-flow pumps, $4000 < N_s < 10000$, and (3) axial pumps, $N_s > 10000$.

The suction specific speed N_{ss} is defined as

$$N_{ss} \equiv \frac{N\,Q^{1/2}}{(NPSH)^{3/4}},$$

where NPSH is the net positive suction head or the total pressure of the flow at the entrance to the pump. It is apparent that cavitation will take place during those operating periods when the NPSH is low. Thus, suction specific speed is used for cavitation warning with the empirically determined cutoff value of $N_{ss} > 8000$ serving this function. Certain techniques discussed in the rotating propulsor section, such as pump staging, design of pumps to operate in a cavitating condition, ventilation, etc., are being considered to reduce the likelihood of cavitation.

A brief review of the theory behind the waterjet will suffice inasmuch as the basic principles of operation are analogous to the general analysis provided for an arbitrary device in Chapter 2. A momentum analysis shows that for steady flow and pressure equilibrium at the exit plane, the thrust developed by a waterjet system is:

$$T_{waterjet} = \int_{A_j} \rho V_j^2 \, dA - \int_{A_i} \rho V_i^2 \, dA, \tag{46}$$

where the subscripts j and i refer to the jet and inlet, respectively. If it is assumed that the jet velocity is uniform over the area of the jet, then the first term of eq. (46) becomes QV_j, where Q is the discharge rate. An assumption of uniform flow entering the inlet results in the following expression:

$$T_{waterjet} = A_j V_j^2 \left(1 - \frac{V_\infty}{V_j}\right). \tag{47}$$

The energy equation for a streamline passing through the pump can be written as follows:

$$H_R + H - H_L - h_s = H_j, \tag{48}$$

where H_R is the total head recovered by the duct inlet and is equal to the total head H_0 of the approaching flow minus the head loss of the inlet, H is the total head developed by the pump, H_L is the internal headloss that occurs in the system, h_s represents the vertical distance that the water must be lifted from the inlet to the centerline of the jet outlet, and H_j is the total head of the jet which (using gage pressures) is equal to $V_j^2/2g$, when discharging into the atmosphere. Assuming uniform flow, so that the inlet kinetic energy correction factor and the momentum correction factor are both equal to unity, the following equation is used to describe the overall efficiency of the waterjet system:

$$\overline{\eta_o} = \frac{\eta_o}{\eta_{pump}} = \frac{2\frac{V_\infty}{V_j}\left(1 - \frac{V_\infty}{V_j}\right)}{\left\{1 - (1-K)\left(\frac{V_\infty}{V_j}\right)^2\right\}} . \quad (50)$$

This result, which is discussed by Contractor[114], indicates that the overall efficiency of the waterjet depends on the pump efficiency, the loss coefficient K, and the velocity ratio, V_∞/V_j. Figure 47 provides a comparison of this efficiency versus the speed ratio for varying loss coefficients.

Brandau[112] provides an excellent summary of the advantages and disadvantages of the waterjet propulsor. Several advantages of this system are:

(1) Elimination of external underwater appendages which would add to total drag.

(2) Elimination of complex right-angle transmission drives.

(3) Reduction in cavitation, vibration, and radiated noise due to greater control over the flow through the impeller.

(4) Increase in steering and maneuvering control which is accomplished directly with the propulsor.

(5) Adaptation for special shallow-draft high speed operations.

(6) Increase in safety for individual swimmers operating in the environment as compared to the hazards of the screw-type device.

The waterjet is, in general, more complex and expensive than the conventional propeller. It is also subject to inlet clogging and less efficient and heavier than the ship screw.

In order to complete the discussion on steady jet-type propulsors which employ a rotating device such as a screw propeller or a pump impeller, the hydronautic counterparts of the turbojet, turboprop or turboshaft, and turbofan engines must be mentioned. The ducted propeller and the waterjet previously discussed actually come closest to representing the hydrodynamic forms of the turboprop and turbofan propulsors, respectively. Again it is difficult to distinguish between the energy source and the actual thruster in these discussions, and the true situation falls short of the desired analogy. In the air-breathing engines, the fluid medium is the same for the prime mover and the thruster, whereas in the marine propulsive system, there generally is no direct use of the water medium in the energy source, but the thruster acts on the water. The prime movers in both cases are essentially the same, a gas turbine-propeller or gas turbine-fan combination. The only direct use of water as a working medium in the energy producer, other than as a thrust augmenter, is with water-reactive metals in a hydroduct application to be discussed below.

The true marine turbojet engine utilizing water or aerated water as the working medium (bubble jet propulsion) has not been fully developed, whereas the gas turbojet, normally employed for atmospheric thrust development, can be used to power the impellers in a waterjet system or to drive a screw propeller by extracting work from the turbine.

Turboshaft engines with "free power turbines" are becoming popular in marine jet propulsion due to their flexibility in output power and rotational speed[208]. With these systems, a plenum-chamber-type inlet is employed to separate the air from the ingested water. The air is then passed through a cycle similar to that of any gas engine and expanded to provide work to drive the water medium (which produces the desired momentum change and thrust). Because the turbine engine is sensitive to back pressure, an exhaust ejector or condensuctor is often placed in the system to reduce the back pressure to a value below that of ambient. A portion of the airflow from the turbo-engine is circulated through the machinery for ventilation and the remaining exhaust gas is directed toward the rear to take advantage of any residual thrust.

In discussing possible propulsion systems for the surface effect ships, Waldo[132], focuses his attention on marine gas turbine engines as the primary power source and either water screws, air screws or waterjets as thrusters. The basic thrusters that are contemplated for use with the gas turbine engine are air propellers, waterjets, supercavitating propellers and supercavitating partially-submerged propellers. In a manner corresponding to that described above, an aircraft-type turbofan engine using the injection of large amounts of water into the by-pass fan discharge duct for thrust augmentation, has been reported on by Davison and Sadowski[208]. This combination is being considered for use in high speed surface effect ships and will provide a decided weight advantage over the waterjet and super-cavitating propeller systems for the power ranges being considered.

Results of the analysis show that the water-augmented turbofan engine can provide almost three times the thrust of the engine without water injection when it is installed on a vehicle with a design speed of fifty knots.

4.4 RAMJET AND PULSEJET PROPULSORS

Unlike the turbojet, turboprop and turbofan, the ramjet and the intermittent or pulsejet fit easily into the thrust generator scheme established, since they have no rotating parts and exhaust directly into the surrounding medium. The underwater ramjet or hydroduct is a propulsive device in which an expanding gas is caused to mix with a flow of water and as a result, additional momentum is imparted to the water by the energy in the gas.

Mottard and Shoemaker conducted a series of tests using a model of an underwater ramjet powered by compressed air and their theoretical analysis and results are contained in Reference 212. Figure 48 shows a sketch of the ramjet with its component parts: diffuser, fuel injector and nozzle. These tests were run with varying forward speeds and air flow rates and proved that this simple device could produce thrust, although the value was small. Efficiencies in the 50 per cent range were attained.

The ramjet operating cycle begins as the water captured by the inlet is diffused and passed into a mixing chamber; the energetic gas is injected at the chamber pressure and temperature, and the water-air mixture is exhausted through the nozzle. Because of the aeration occurring in mixing, the water-air combination is less dense than the water alone and the exit velocity must exceed the forward speed resulting in a thrust force. Assuming steady flow, the basic thrust equation is applicable in the following form:

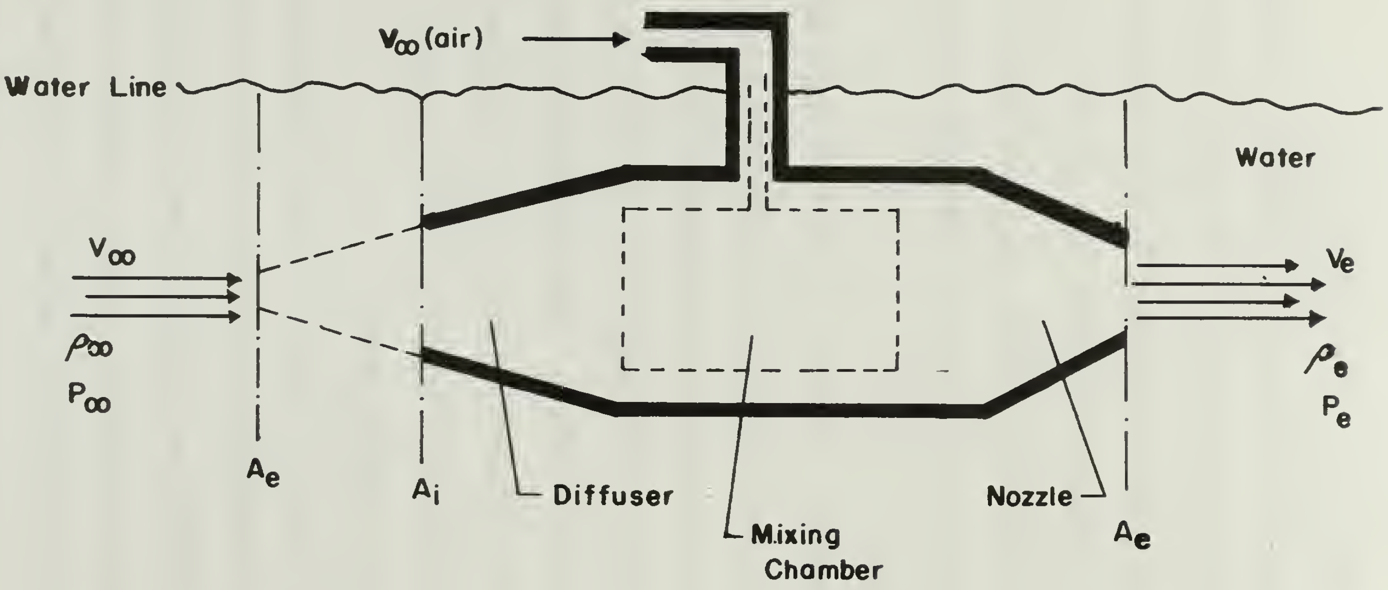


FIGURE 48 SKETCH OF HYDRODUCT (RAMJET)
(REF. 212)

$$T = \dot{m}_{H_2O}(V_e - V_\infty) + \dot{m}_{air}(V_e - V_\infty) + A_e(p_e - p_\infty). \tag{51}$$

A thrust coefficient based on the capture area A_c (see Figure 49), is defined as follows:

$$C_{T_c} = \frac{T}{\frac{1}{2}\rho_{H_2O} V_\infty^2 A_c}$$

or

$$C_{T_c} = 2\left(1 + \frac{\dot{m}_{air}}{\dot{m}_{H_2O}}\right)\left(\frac{V_e}{V_\infty} - 1\right) + \frac{A_e(p_e - p_\infty)}{\frac{1}{2}\rho_{H_2O} V_\infty^2 A_c}. \tag{52}$$

Since the exit flow is subsonic, the pressure at the exit is equal to the ambient pressure and the pressure term in the above equation goes to zero.

Application of Bernoulli's theorem yields:

$$p_{t_m} = p_\infty + \frac{1}{2}\rho_{H_2O} V_\infty^2, \tag{53}$$

where p_{t_m} is the total pressure in the mixing chamber. The mixing process is assumed to occur homogeneously without any loss in total pressure. The nozzle total pressure is also assumed constant and equal to that in the mixing chamber. Thus,

$$p_{t_m} = p_e + \frac{1}{2}\rho_e V_e^2, \tag{54}$$

where ρ_e is the density of the air-water mixture at the exit plane. Combining eqs. (53) and (54) and introducing $p_e = p_\infty$, we obtain:

$$p_\infty + \frac{1}{2}\rho_{H_2O} V_\infty^2 = p_\infty + \frac{1}{2}\rho_e V_e^2$$

or

$$\frac{V_e}{V_\infty} = \left(\frac{\rho_{H_2O}}{\rho_e}\right)^{1/2}. \tag{55}$$

The density ratio at any station is

$$\frac{\rho_{H_2O}}{\rho_e} \quad \frac{\left(1 + \dfrac{\dot{m}_{air}}{\dot{m}_{H_2O}} \dfrac{\rho_{H_2O}}{\rho_{air}}\right)}{\left(1 + \dfrac{\dot{m}_{air}}{\dot{m}_{H_2O}}\right)} . \qquad (56)$$

The velocity ratio is given by combining eqs. (55) and (56) and is

$$\frac{V_e}{V_\infty} = \left[\frac{\left(1 + \dfrac{\dot{m}_{air}}{\dot{m}_{H_2O}} \dfrac{\rho_{H_2O}}{\rho_{air}}\right)}{\left(1 + \dfrac{\dot{m}_{air}}{\dot{m}_{H_2O}}\right)}\right]^{1/2} . \qquad (57)$$

This velocity ratio can now be used with equation (52) to solve for the thrust produced by the system. However, it is more common to convert the thrust coefficient to C_{T_f}, the thrust coefficient based on frontal area, by multiplying the expression for C_{T_a} by the area ratios, A_c/A_e and A_e/A_f. The first of these ratios is obtained through continuity,

$$\frac{A_c}{A_e} = \left[\frac{V_e/V_\infty}{1 + \left(\dfrac{\dot{m}_{air}}{\dot{m}_{H_2O}}\right)\left(\dfrac{\rho_{H_2O}}{\rho_{air}}\right)}\right]$$

whereas the area ratio A_e/A_f is given by the model dimensions. The final relationship for C_{T_f} is

$$C_{T_f} = \frac{T}{\frac{1}{2} \rho_{H_2O} V_\infty^2 A_f}$$

and is plotted in Figure 49 which gives a comparison of theory and test results as determined by Mottard and Shoemaker.

A series of pulsed hydrodynamic jet propulsion systems is pictured in Figure 50 and described in detail by Schuster, et al[213]. The typical work cycle can be broken into two parts: (1) an expulsion stroke in which the water is driven out the rear of the duct in the form of a jet, the driving action being done by a mechanical or hydrodynamic piston or by a gas shield and (2) a suction stroke in which the chamber is filled by water flowing in from all sides. The expulsion phase is accomplished by expanding combustion gases which are produced in the combustion chamber.

There is no exact theoretical analysis for estimating the pulsejet performance characteristics. The thrust is proportional to the product of the increase in velocity of the water and the average mass rate of flow of the gas and water mixtures flowing through the tube, but the exact relationship is not known due to the burning rates and escape of gases in the system.

Several interesting jet propulsion devices which operate in the manner of a hydroduct have been patented by C. A. Gongwer[18]. In his earliest device, Figure 51, water from the surrounding medium enters at the front through a mouth and passes into a reacting chamber. A water-reactive material is injected and the spontaneous reaction forms steam. The water-reactive agent could be molten lithium, magnesium or aluminum. Most of the water taken in flows through the device and leaves by an exit nozzle which ejects the water at a higher velocity than it had on entrance. A stream of steam is injected into the water flow to increase the velocity of

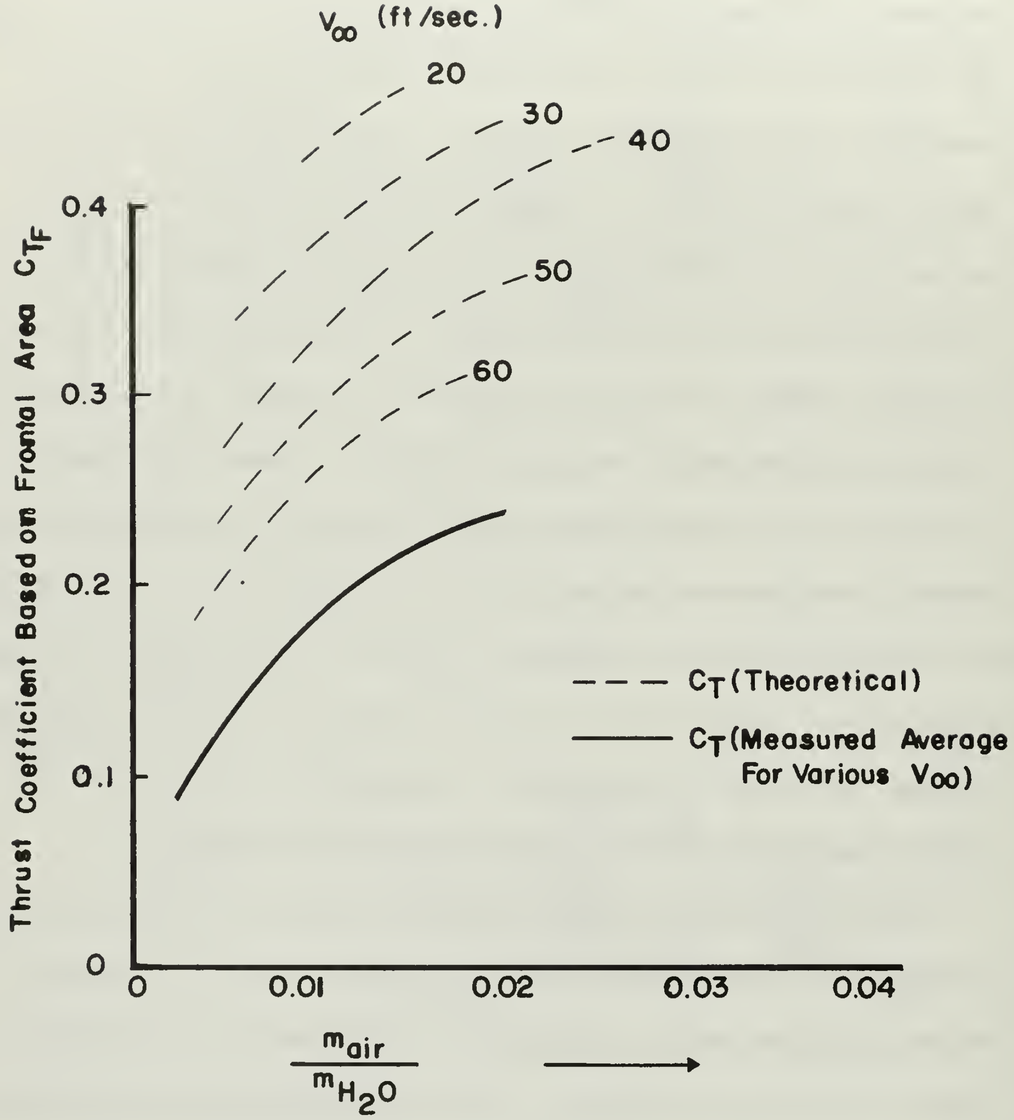
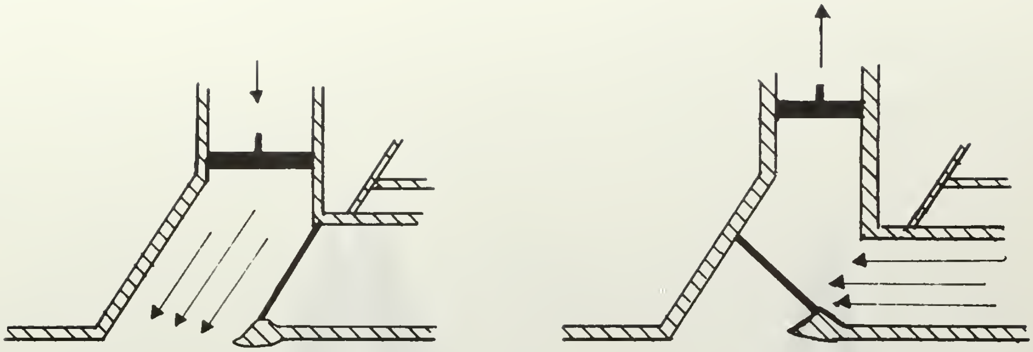
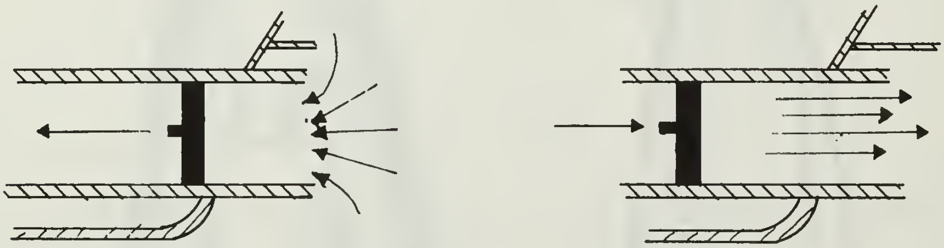


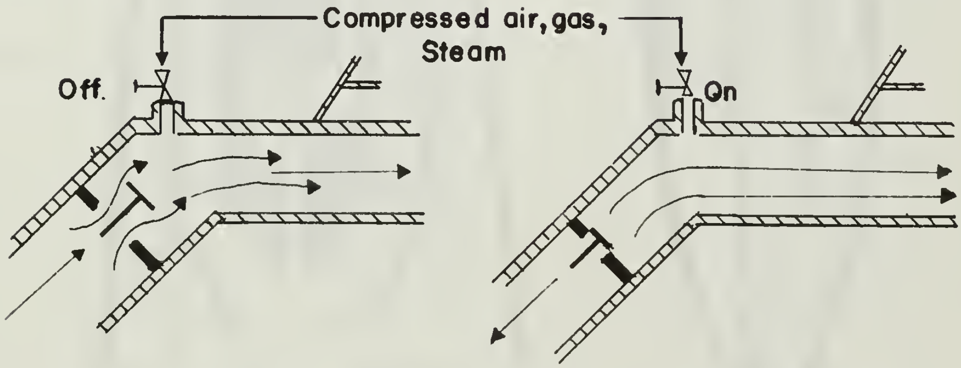
FIGURE 49 COMPARISON OF THEORETICAL AND MEASURED THRUST COEFFICIENTS FOR RAMJET (REF. 212)



a. Pulsing Piston – Flapper Valve Device



b. Simple Piston Pulse Jet



c. Poppet Valve System Using Compressed Air, Gas, or Steam

FIGURE 50 SKETCHES OF VARIOUS UNSTEADY HYDRAULIC PULSEJET PROPULSORS (REF. 213)

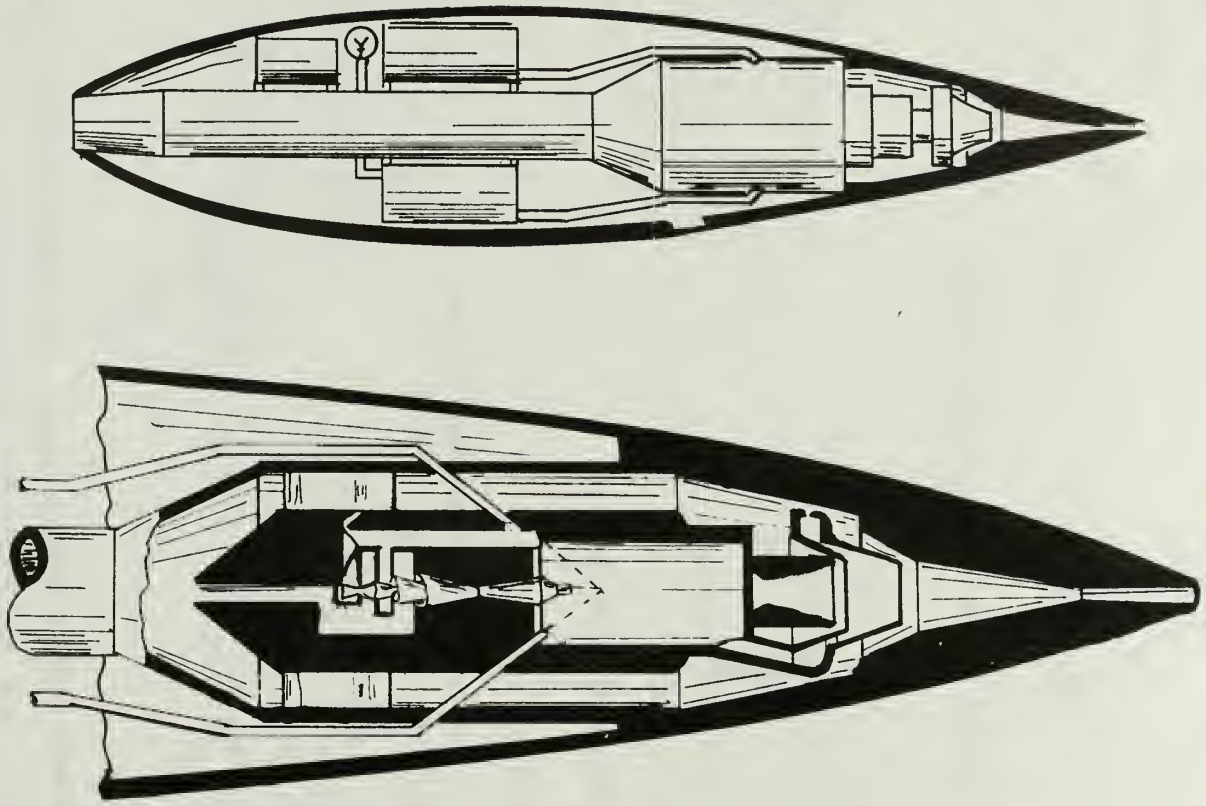


FIGURE 51 UNDERWATER JET PROPULSION DEVICE
(REF. 18)

ejected water. Since most of the steam condenses when mixed with the water, a very low pressure exists at the entrance to the exhaust nozzle, as determined by the temperature of the water condensing the steam.

In another device called a hydroductor, (shown in Figure 52), the water flows from an entrance duct into a reaction region where a self-combustible charge is located. The heat of combustion of the propellant vaporizes the water and this steam is forced rearward through a nozzle. A condensuctor is attached at this point to allow operation in deep water. The principle of this device will be explained in Section 4.6. A typical reaction is as follows:

$$8Al + 3KClO_4 \rightarrow 4Al_2O_3 + 3KCl + 2.49 \text{ kcal/gm. of propellant.}$$

The products of combustion do not include any gaseous noncondensible products and only those reactants which have a low molecular weight and produce solid or liquid combustion products are recommended.

4.5 ROCKET PROPULSORS

Recently the underwater rocket has seriously been considered as a desirable propulsor for high speed weapons systems such as torpedoes. Its intended use against short range, fast-moving targets which operate at great depths makes the underwater rocket a high priority item in research and development facilities. However, Lawrence and Beauregard state in Reference 180 that as yet no definitive system of exact equations has been developed for underwater rocket propulsion. By testing compressed nitrogen rockets in various nozzle configurations, these investigators concluded that the conventional thrust and flow relationships for rockets cannot be applied directly to underwater

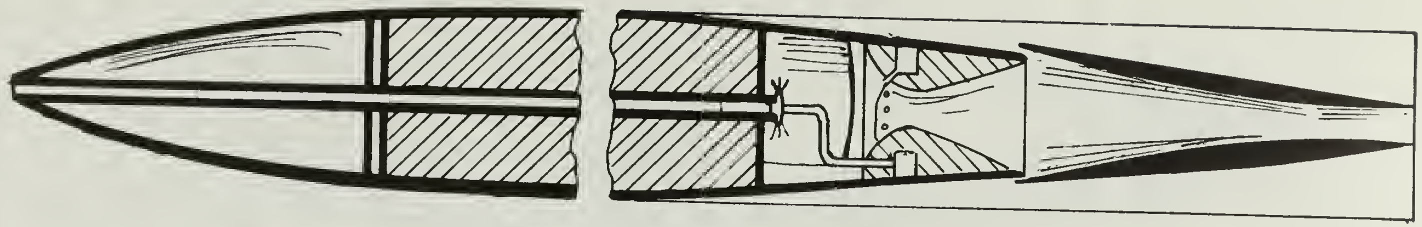


FIGURE 52 HYDRODUCTOR (REF. 193)

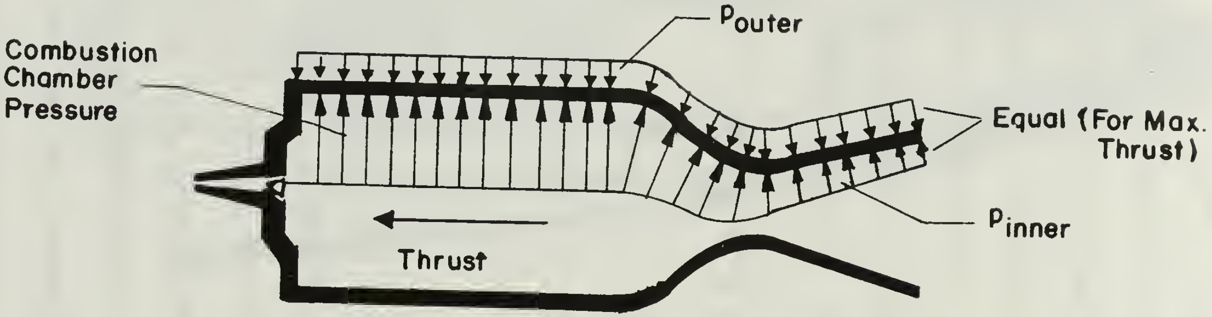


FIGURE 53 TYPICAL ROCKET MOTOR SHOWING PRESSURE DISTRIBUTIONS

rockets due to the large pressure fluctuations and separation along the nozzle which result from the flow in the water medium. Table IV shows a comparison of the effects of air and water on the performance of rockets, and a large deviation is to be noted.

The theoretical thrust and propulsive efficiency for a rocket operating in any medium are given by eqs. (8) and (17) in Chapter 2. An alternate method of developing the thrust of a rocket motor is to consider the resultant of the pressure forces acting on the interior and exterior surfaces of the device. The internal absolute pressures decrease in the direction of flow because of the expansion through the nozzle. The external pressure is a constant and equal to that of the surroundings P_a, which is relatively low compared to the large pressures developed in the chamber. The axial thrust T can be found by taking the vector sum of all the axial components of the internal and external pressures over the surfaces on which they act; i.e.,

$$T = \int_{A_{outer}} p_{outer} \, dA_x + \int_{A_{inner}} p_{inner} \, dA_x \, . \tag{58}$$

Figure 53 shows a schematic of a typical rocket motor and these pressure forces are indicated in a qualitative manner.

We now return to the thrust equation for a rocket:

$$T_{rocket} = \dot{m}_e V_e + A_e (p_e - p_\infty) \tag{8}$$

$$= \dot{m}_e V_j \, .$$

TABLE IV. COMPARISON OF ROCKET NOZZLE THRUST COEFFICIENTS AND SEPARATION AREA RATIOS IN AIR AND WATER ENVIRONMENTS (REF 180)

P_c = chamber pressure

P_a = ambient pressure (1 atm)

P_c (psia)	P_c/P_a	Separation Area Ratio (ε_s)			Nozzle Thrust Coefficient (C_F)			
		Air	Water		Air	Water		Deviation caused by submergence** (%)
			Minimum	Maximum		Minimum*	Maximum†	
450	30.3	7.4	<7.2	10.8	1.377	1.291	1.380	-6.3 to 0.2
1010	68.4	13.7	<7.0	21.8	1.465	1.371	1.516	-6.4 to 3.5
1120	75.9	14.7	12	53.7	1.476	1.012	1.500	-31.2 to 1.6
1430	97.0	17.7	<8.3	43.8	1.498	1.266	1.547	-15.5 to 3.3
1950	132	22.3	<8.2	52.6	1.525	1.326	1.571	-13.0 to 3.0

* Calculated from maximum ε_s

† Based on minimum ε_s except at P_c = 1950 psia where "optimum" ε_s is used; optimum occurs where separation pressure (P_s) = 1 atm.

** $100 \left[C_F(\text{water}) - C_F(\text{air})\right]/C_F(\text{air})$.

Unlike the jet, the pressure term is of great significance in the rocket thrust determination. As the vehicle descends to greater depths, the ambient pressure increases rapidly and acts to reduce the thrust. This presents an excellent opportunity for the use of a condensuctor whose primary purpose is the apparent reduction of the back pressure, thus allowing exhausting of the combustion products directly into the surrounding water.

The underwater rocket has been somewhat neglected in comparison to the space rocket, but presently a large number of research projects are concentrating on the various aspects of this device. Patrick[37] at the Naval Ordnance Test Station in Pasadena has been conducting investigations into the unsteady behavior of gas jets in the water environment and the possibility of augmenting the thrust of a rocket by discharging noncondensable gases over the tail cone. Numerous studies on space rockets are continuing to add valuable information for underwater applications, both as to type of propellants and thrust augmenting procedures.

Greiner[21] presents a list of underwater propellants and their theoretical performance parameters. This compilation is included as Table V in this report and indicates that certain metals are the best propellant performers. Premelting the propellant, using it in powder form or as slurry which can be pumped into the chamber are suggested means of improving underwater rocket performance.

Preliminary research has shown that unlike the air rocket, the heating value of the propellant rather than the specific impulse is of prime importance. The limited space available for fuel and oxidant aboard an underwater rocket device requires a high energy density, or large BTU-to-pound-of-propellant ratio.

TABLE V. Approximate theoretical performances of some underwater propellants. (Formulations diluted with water to decrease combustion temperatures to about 1800 F; results in horsepower for 20.4/1 expansion ratio) (Ref. 220)

No.	Fuel	Carried oxidizer	hp hr/ft^3	hp-hr/lb
1	Al	...a	114	0.70
2	Zr	...a	106	0.27
3	Al	LiClO	78	0.57
4	Mg	...a	71	0.64
5	Mg	LiClO	60	0.55
6	Zr	BrF_5	59	0.29
7	Al	H_2O_2 (90%)	55	0.55
8	Mg	H_2O_2 (90%)	50	0.58
9	Li	LiClO	45	0.72
10	Li	...a	41	1.27
11	Li	H_2O_2 (90%)	40	0.68
12	N_2H_4	H_2O_2 (90%)	28	0.36
13	diesel fuel	H_2O_2 (90%)	28	0.35
14	alcohol (92.5%)	H_2O_2 (90%)	26	0.34
15	hydrazine monopropellant[b]	...	23	0.28
16	typical solid propellant	...	23	0.31
17	Na	$LiCL_4O$	21	0.31
18	H_2O_2	...	12	0.14
19	Na	H_2O_2 (90%)	10	0.34
20	Na	...a	5	0.24
21	alcohol(92.5%)[c]	compressed air	3	0.16

[a] Free water used as oxidizer as well as diluent.

[b] Liquid-monopropellant formulation, 8% N_2H_4, 72% $N_2H_5NO_3$, 20% H_2O

[c] Diluent water carried.

The entire field of hydropropulsion using non-rotating machinery has opened up as methods have been discovered to reduce the jet velocity and thereby increase the inherently poor efficiency of the devices. One method of increasing the thrust while decreasing the exit velocity is embodied in a device called the condensuctor which is discussed next.

4.6 CONDENSUCTOR

The condensuctor is a two-phase jet pump which is capable of simultaneously condensing and pumping a liquid and vapor mixture to produce an exit stagnation pressure equal to or greater than the inlet total pressures of either inlet stream. It has been studied extensively by G. A. Brown of the J. Kaye Company. References 189-192 contain descriptive and experimental information concerning this device. See Figure 54 for a schematic diagram of the flow conditions existing through the condensuctor and the pressure distributions at various stations.

Essentially the condensuctor can be termed a condenser ejector which condenses and cools the low pressure exhaust from a turbine or similar prime mover, and raises the pressure of a stream of water which enters the device through a separate nozzle. The level to which the pressure of the exhaust mixture is lifted must be sufficient to allow discharge into the surrounding sea medium at its existing ambient pressure. In effect, this mechanism is a specially designed mixing tube which is attached to a gas turbine or rocket discharge jet or other hot gas stream. A high velocity jet of cold seawater (either pumped in or obtained by ram effect) is mixed with the jet exhaust in order to condense the water vapor in the mixture and to cool the gases. This temperature decrease is actually the controlling

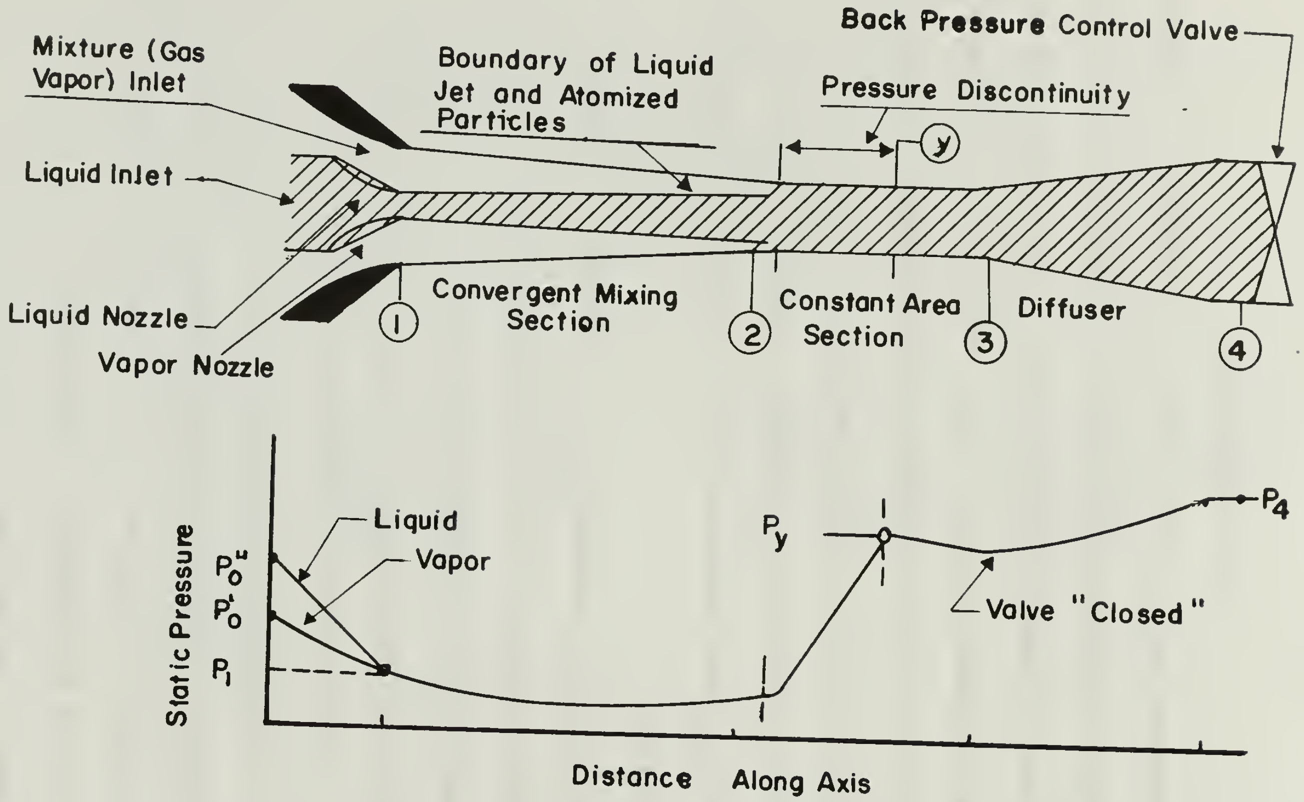


FIGURE 54 TYPICAL CONDENSING EJECTOR (CONDENSUCTOR) PROCESS AND PRESSURE DISTRIBUTION (REF.191)

factor in the process of reducing the velocity of the exhaust stream, thereby effectively reducing the back pressure. A normal shock wave forms in the mixing tube permitting discharge against a high ambient pressure. The primary function of the condensing ejector is to allow the jet propulsor to operate with an extremely low back pressure despite the very high ambient pressures that exist at great depths in the ocean.

The basic advantage of the condensuctor is the fact that it is fairly insensitive to depth and thus, can be used at various levels of the water environment. The back pressure does not necessitate the production of excessively high chamber pressures with this device included in the propulsion system of a marine vehicle.

The variable area condensuctor which is the model in Reference 190, is designed to operate with a completely condensable vapor stream. In order to obtain results for a variety of contraction ratios of the tube, and to allow comparison of performance, the vapor and the liquid streams are considered to remain unmixed until they reach the upstream edge of the shock zone where condensation occurs. Results of this study indicate that the exit pressure from the device is greater than both the inlet pressure of the liquid and gas, and hence, serve to substantiate the effectiveness of this propulsor. For a more detailed analysis of the condensuctor, see Reference 190.

Reference 191 is an attempt to determine the effect of having non-condensable gases present in the mixture stream as a result of combustion. The results of this project reveal that a pressure increase is still possible with as much as 5 per cent (by mass) of non-condensable gas in the system.

CHAPTER 5

COMPARISON AND APPLICATION OF MARINE PROPULSORS

In the preceding sections, a number of thrust devices suitable for use with marine systems have been described and analyzed. The important performance parameters have been defined and applied to the propulsors, where relevant in order to arrive at an evaluation of the basic performance of the individual devices. The results of many investigations have been studied and data concerning the devices has been presented in graphs and charts in order to provide an overall idea of the performance of each individual device. A comparison of the various marine propulsors based on this test data (and the theory, where test results are inconclusive) is now possible. A brief discussion of the missions that these mechanisms can perform constitutes the basis of this concluding chapter.

5.1 OVERALL SYSTEM COMPATIBILITY

In discussing the missions assigned and the various vehicles and weapons systems needed to accomplish these missions, there are numerous factors which must be considered. Speed, depth capability, maneuverability, noise minimization, endurance, range or any other single performance parameter could control the selection of the propulsor for a particular mission. This paper is intended as a guide to the preliminary mating of propulsor and vehicle. One must realize that detailed investigations of these vehicles or weapons systems would require an integrated "systems analysis" covering specific requirements. Reference 13 is pertinent reading for propulsor selection techniques.

5.2 GENERAL COMPARISON

By deriving thrust, torque, efficiency, and thrust augmentation relationships for the various devices, a qualitative performance relationship was sought between the thrust generators. When the two general categories of marine propulsors, the rotating-type machines and jet devices, are compared on an efficiency basis, the results indicate that in the present state of marine technology and range of vehicle speeds, the screw propeller and its various modifications enjoy a definite advantage over the jet propulsors. However, current investigations seeking to improve the performance of jet thrusters are gradually eliminating this variance in efficiencies. As a result, there has been an increased emphasis on the design and testing of novel jet devices. Since the jet propulsor was essentially ignored for a long period of time, while the rotating propulsor received the bulk of attention in this field, the jet-type device is only now appearing as a real competitor for the propeller. Within the next decade, the anticipated substantial increase in the efficiency of jet propulsors, when combined with the thrust capabilities of this device, should result in its emergence as the prominent thrust generator in the marine environment.

As indicated in Figure 21, the ideal propulsive efficiency of a typical conventional screw is about 70 per cent at its design speed. This may be a conservative figure according to the results of other studies; however, it provides a basis for comparison of efficiency with other thrusters. The cycloidal propeller, which is reportedly about 50 per cent effective, and the undulating plates, do not approach the efficiency of the normal propeller, but, as pointed out, they serve specific purposes and their inefficiency does not mean they are not useful.

Supercavitating and ventilated propellers can be grouped together since one is an artificial model of the other. Theory has predicted propulsive efficiencies in the range of 80 to 85 per cent for these devices, but so far they have not generally proven to be this efficient. They compare favorably with the conventional propellers in thrust and torque production and are a definite improvement at high speeds in shallow waters.

It is evident that the propulsive power of the cycloidal propeller is limited, but this is considered to be a natural result of the basic purpose of the propeller which was intended to serve as a control system as well as a thrust device. It may not measure up to the conventional water screw as far as performance is concerned, but it does have a maneuverability advantage over the screw propeller. This results from the fact that the thrust produced by the cycloidal propeller may be vectored in any desired direction, without changing the rotative direction of the engine, by simple manipulation of a mechanism which alters the blade angles. This feature eliminates the need for a rudder or other steering device and, thus reduces the drag due to external appendages. A disadvantage of the cycloidal propeller is the increased complexity due to the intricate gearing mechanisms that must be employed.

Although it is not anticipated that cycloidal propellers will supersede the conventional water screw in importance, they do have many special applications, such as low speed ships concerned primarily with control and maneuverability as compared to high speed planing-type ships.

The practicality of the concept of swimming plates for applied use in marine systems has not as yet been proven; however, the advantages of the device are many; e.g., (1) no shaft-sealing problems, (2) low acoustic noise level, (3) small idling drag, (4) good thrust control, (5) safe environment for swimmers, (6) high efficiencies anticipated, and (7) the device is excellent for operations in weeds and muddy, shallow water. A possible disadvantage, depending on the viewpoint, is the limitation of these devices to low speed marine vehicles.

Botman[133] recommends application of the principle of undulating plates for use with walls forming a duct of variable width. He presents two specific designs which warrant further investigation. It is felt that the waving plate has good potential and can be useful in several applications in a low-speed, shallow water environment.

Counterrotating propellers are more efficient than the simple water screw for propulsion purposes since the losses due to rotation of the fluid are minimized. Figure 22 shows a typical value of 83 per cent for propulsive efficiency and about the same thrust and torque capabilities as the single ship screw. The Tandem Propeller System (TPS), although not as efficient as the simple screw, has added advantages, such as increased controllability, which makes it very useful for specific missions. This system is rapidly approaching operational readiness and will be available to propel a deep-diving vehicle in the very near future.

Although psuedo blades are still very much in the developmental stage, preliminary tests indicate great potential. Augmentation of thrust with the ducts designed by Avellone, et al.[174], has shown a typical increase of 20 per cent by the rotating device over the pure jet model and close to 100 per cent increase in thrust by the ducted device as compared to the unducted. See Figure 36.

Figure 37 shows that the psuedo-blade has a decided advantage as to propulsive efficiency when compared to a rocket motor.

Figure 43 shows that the ducted propeller has a slight advantage over the unducted model due to the additional thrust produced by the shroud. Figure 45 indicates that the ducted subcavitating propeller can operate at efficiencies of 60 per cent while producing a greater thrust than the normal screw.

In general, jet propulsors are not as effective as rotating devices. The water jet will require further improvements in ducting and lessening of losses in the system prior to becoming an <u>efficient device</u>. However, it is presently used to advantage in some small craft where efficiency is not the primary factor. The waterjet has found excellent use at high speeds and is very maneuverable (by rotating the exit jet). The waterjet is also quite advantageous for shallow water operation in weed-infested and swampy terrain. Presently, overall efficiencies on the order of 70 per cent are predicted, but no substantiating empirical data are available. The thrusting ability of this device is impressive and makes it desirable for high speed craft. Rocket and air-turbine engines also need further sophistication before they can be used interchangeably with rotating devices. The condensing ejector is a stride forward in bringing the underwater rocket and jet-type propulsor to full utilization.

5.3 MISSION AVAILABILITY

The types of missions to be performed by present and future marine systems can be conveniently separated into two general classes according to the sphere of operation; i.e., surface missions and deep submergence tasks. Some propulsors are, by their very nature, limited in their mission capability to one of these types of missions; e.g., the supercavitating and ventilated propellers and ramjets are primarily designed for use with shallow water or surface vehicles and to use them otherwise could prove very inefficient. Many devices can be utilized in either locale with varying degrees of effectiveness; e.g., swimming plates can be used to advantage in either shallow or deep water, the safety factor being important in the first instance, and the elimination of the sealing problem at high pressures making this device attractive for deep-diving vehicles. Tests of many of these mechanisms, especially the jet devices, are presently being conducted at an intensive pace and their ultimate overall ability is still increasing.

A second mission requirement which may be a determining factor in selecting the marine propulsor to be used with a particular system is the design range of operating speeds. High speed vehicles generally require a jet-type device for optimum performance and the waterjet, rocket and ramjet would appear to meet the requirements of the high speed vehicles to a satisfactory degree. Low speed vehicles, such as the support ships for research and rescue or search systems, which need good power and control features, can employ the cycloidal propeller and the conventional screw propeller to advantage. The base-vented propeller employs a principle of design that alleviates problems in the speed range from start to cruise and should prove of vast significance in future marine vehicle development.

Maneuverability is a desirable property in many underwater missions and the Tandem Propeller System, which uses the counter-rotating blade concept, finds good utilization under these circumstances. The use of thrust vector control with a jet device will also assist in providing controllability of marine vehicles. Cycloidal propellers should also prove very useful for maneuverability purposes.

5.4 APPLICATION OF PROPULSORS TO DESIGNATED MARINE VEHICLES

Research vehicles, such as the URV and the Dolphin, require propulsion devices which are capable of deep submergence operation. Range, endurance and maneuverability are also desired characteristics in this type of vehicle. The Tandem Propeller System embodies all these traits and should prove to be an effective thrust and control device when combined with an oceanographic research vehicle.

Rescue and search vehicles have propulsion requirements similar to those of research vehicles and here again the TPS or cycloidal propeller should prove valuable. The intricate process of "matching hatches" in rescue missions will require that a vehicle possess nearly spontaneous control in all directions.

Deep diving submarines will primarily be concerned with efficient operation at great depths and speed, range and endurance qualities. The condensuctor will be an advantageous device for this mission if its excessive noise radiation can be minimized. The use of the ramjet or pulsejet as a secondary thrust device, capable of providing high burst speeds, is also a possibility in the near future.

For propelling torpedoes and similar guided and unguided weapons, the rockets and condensuctor-type propulsors will be well-adapted for use against high speed, deep-diving targets. Their high noise radiation will restrict them to short range point-blank missions in this regard.

With respect to the high-speed surface vehicles, such as the hydrofoil, SES, and CAB systems, supercavitating or ventilated propellers, waterjets, ramjets or pulsejets, or water-augmented air-turbo engines appear to offer the optimal advantages for propulsion purposes. Inasmuch as cavitation is most severe under conditions of high rotative speeds and shallow depths, any device which delays its inception or eliminates it completely will be extremely valuable.

Future research in the field of marine propulsion may establish an absolute scale for performance. Such an accomplishment would eventually present a more complete comparison of marine propulsors.

As a result of the information accumulated in this study, some overall guidelines have been arrived at on the basis of the physical descriptions and analyses of the available thrust devices. An extensive bibliography is provided the reader who desires more detailed information for further studies of the present state-of-the-art in marine propulsion.

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APPENDIX A

DRAG REDUCTION TECHNIQUES

While many investigators are searching for dramatic increases in the performance of marine vehicles through the development of more powerful propulsion systems, it is quite possible that the indirect approach of drag reduction will prove to be as valuable with regard to large-scale performance improvements. The significant advances already realized in marine technology have resulted primarily from continued research in propulsion methods; however, due to weight and volume restrictions, performance limits are rapidly being reached in this direction. Although the principles involved in drag reduction are not new, recent discoveries have promoted great interest in this field and it appears that tremendous practical gains are imminent.

As a result of the relatively high viscous nature of seawater, excessive drag forces are encountered when operating at or below the surface of the ocean. Of primary hydrodynamic importance in this regard is that portion of the resistance attributable to skin friction. In addition to energy absorption due to frictional drag effects, a body operating in a water environment must expend otherwise useful power overcoming wave drag, cavitation drag, separation or pressure drag, and induced drag resulting from hydrodynamic lift forces and angle of attack. However, as indicated above, skin friction resistance absorbs the most power and therefore, researchers have concentrated on finding methods of reducing this type of drag.

Even properly streamlined marine weapons systems are subject to skin friction drag to some degree since in performing useful missions, they necessarily operate at Reynolds numbers conducive to the formation of turbulent boundary layer flow. The excessive momentum transport that occurs in the turbulent layer is the actual mechanism that causes the high frictional drag. Numerous techniques have been offered as means of reducing this transport of momentum, but they can all be placed in either of two basic categories: (1) delay of the transition to turbulent flow by maintaining laminar boundary layer conditions as long as possible along the surface of the underwater body, and (2) modification of the turbulent flow after it has once been established to bring about laminar conditions, or at least reduce the intensity of turbulence. Figure A-1, which is reproduced from Reference 87, points out the marked reduction in friction drag that can be attained by preserving laminar flow in the boundary layer.

In general, most liquids may be assumed to be Newtonian in nature; i.e., a linear relationship exists between shear stress and the shearing strain rate or rate of angular deformation. This may be expressed as follows:

$$\tau_{xy} = \mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right),$$

where τ_{xy} is the shear stress, or force per unit area, $\partial u/\partial y$ and $\partial v/\partial x$ represent the velocity gradients and μ is the constant of proportionality between the two, otherwise known as the viscosity.

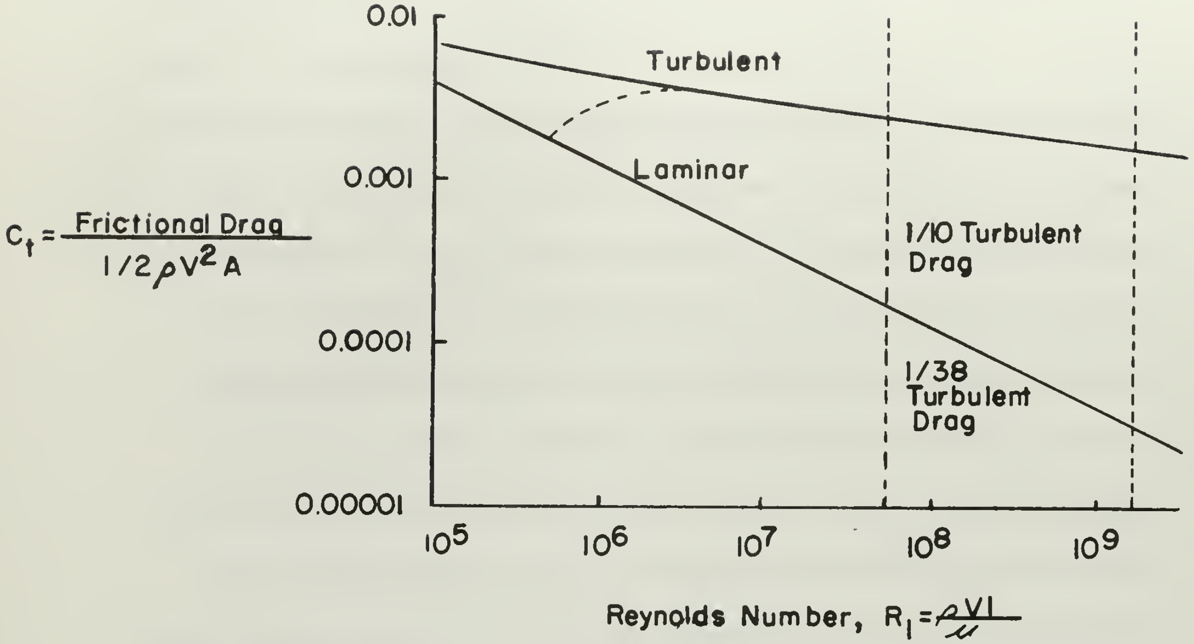

FIGURE A-1 DRAG COEFFICIENT AS A FUNCTION OF REYNOLDS NUMBER (REF. 87)

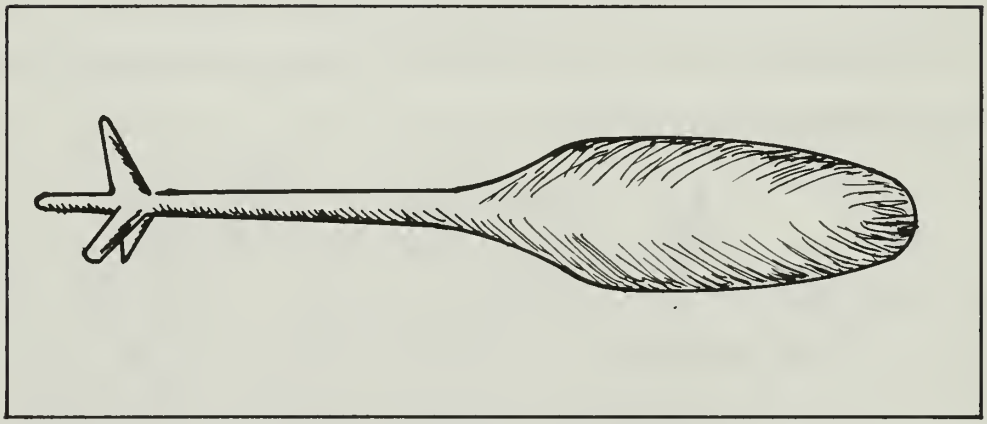

FIGURE A-2 NORTH AMERICAN AVIATION LAMINAR-FLOW BODY, DOLPHIN I (REF. 87)

If y is measured perpendicular to the surface, then $\left.dv/dx\right|_{y=0} = 0$ and:

$$\tau_{wall} = \mu \left(du/dy \right)_{y=0} ,$$

where the subscript y = 0 indicates that we are referring to the normal velocity gradient on the surface. It follows from this that the viscous drag due to skin friction is given by:

$$D_f = b \int_{x=0}^{\ell} \tau_{xy} \, dx ,$$

where b is the height of the body element under discussion and the integration is accomplished over the entire length ℓ of the body, or

$$D_f = b\mu \int_{x=0}^{\ell} \left(du/dy \right)_{y=0} dx ,$$

where the viscosity is assumed constant along the body surface. Obviously, the total friction drag is dependent on the velocity profile in the boundary layer as well as the length of the body. Pressure drag resulting from separation of flow in the boundary layer would considerably alter the above drag expression. The frictional drag rises sharply when laminar flow breaks down. When separation or transition to turbulent flow occurs, the momentum transport changes the velocity profile, increasing $\left(du/dy \right)_{y=0}$. Schlicting[101] presents a detailed description of separation and its attendant drag increment as well as a qualitative study of the resistance aspects of turbulent flow.

Many of the conventional drag reduction techniques seek to stabilize the laminar boundary layer by eliminating disturbances of all magnitudes from the flow. Since transition to turbulence can be caused to occur at any Renolds number if a sufficiently violent disturbance takes place, it is desirable to prevent small disturbances from growing into large ones by dampening methods. Stabilization techniques are designed to increase the viscous forces by altering the velocity profile and thus, delay transition.

From the above discussion, it is obvious that significant reduction of frictional drag can be accomplished if the flow is induced to remain laminar in nature, or if the transition to turbulent flow is delayed as long as possible. The proposed techniques of drag reduction in this manner include the following: (1) shape optimization, (2) compliant skin surfaces, (3) suction of the boundary layer, (4) enclosure of the body in gas-filled cavities, and (5) heating or cooling of the boundary layer. Before discussing each of these techniques, it is important to consider what the various factors are that influence the transition from laminar to turbulent boundary layers. Of course, the Reynolds number is of utmost importance and, holding everything else constant and increasing the Reynolds number will eventually cause the boundary layer to become turbulent. As the critical Reynolds number is approached, the viscous properties have a smaller effect compared to the inertial forces and disturbances are not readily damped out. Negative pressure gradients which are favorable from the standpoint of avoiding flow separation, have a stabilizing effect on the flow since they cause velocity profiles which have high viscous forces near the wall thus causing a delay in transition. If the ambient turbulence level or ratio of the average magnitude of fluctuations to the mean free stream velocity of the surrounding medium is high, there is a greater chance that transition to turbulent flow will take place. In the water environment, insufficient evidence is available at the present time to specify with accuracy the turbulence level at a given depth. Of course, if the submerged body is rough along its surface, the likelihood of transition is increased considerably.

(1) Shape Optimization: Carmichael[78] presents a detailed discussion of the reduction of friction drag strictly by geometric means. Figure A-2 is a sketch of the North American Aviation shaped vehicle called the DOLPHIN I, which was obtained by rotating a NACA 66 series air-foil, to construct the body of revolution. Assuming the shaped body has a sufficiently smooth surface, it is possible to design it such that a favorable pressure gradient exists over a large portion of its length, thus promoting laminar flow over most of the wetted surface of the vehicle and reducing friction drag substantially.

The obvious advantage of this method of drag reduction is simplicity due to the absence of any additional moving parts. A drawback in body shape optimization is the fact that the resultant unconventional shape would require an overall and drastic change in the permanent configuration of present weapons system components. A further deterrent to the practical use of this technique is the requirement for increased care in handling the body to avoid dents, scratches and surface defacement that might destroy the laminar flow.

(2) Compliant Skin Boundaries: The concept of compliant surfaces was developed by Dr. M. KRAMER[91]. Basically, it involves the use of a soft rubber surface containing numerous fluid passages. This surface will theoretically dampen any small disturbances in the flow resulting in the maintenance of a laminar boundary layer over a

greater portion of the body length. The idea for such a device was derived from observations of the flow over the skin of aquatic animals like the porpoise. A commercial product called 'Lamiflo', invented by Dr. KRAMER, was tested by the Underwater Ordnance Department at NOTS and the results were contrary to theoretical expectations. Although tests have not yet shown this method to be effective, it is believed that a flexible boundary is capable of significant drag reductions, not through the physical dampening of disturbances as might be imagined, but rather by altering the phase relations between the pressure and the velocity in the vicinity of the surface wall. It is speculated that this active property of the wall will serve to change the nature of the stresses and eliminate the critical Reynolds number altogether.

As with the shape optimization method, compliant boundaries are attractive due to their inherent simplicity, but handling sensitivity is again a problem since it is believed that even slight wrinkling of the surface will increase the drag rather than decrease it.

(3) Suction of the Boundary Layer: Prandtl,[40,73] in his early works on fluid flow properties performed experiments showing that large drag reductions were feasible utilizing small-width discrete slots to suck fluid from the boundary layer near the surface of a body. This process serves to extend the laminar flow well beyond the initial critical Reynolds number by reducing the thickness of the boundary layer, thus increasing the flow stability. It also alters the velocity profile by sucking away the low momentum fluid next to the wall. This normally causes an increase in skin friction over the laminar case, but less friction compared to that existing in turbulent flow.

With the use of the suction method, it is very important that the surface be kept smooth for maximum effectiveness. This restrictive characteristic of sensitivity to smoothness can be lessened by the use of wider slots which will reduce the susceptibility of the system to clogging due to ingestion of foreign materials such as algae, sea weeds, etc. Research in boundary layer control on airfoils has produced excellent results and indicates that increased suction on the upper surface near the end of a body where an adverse pressure gradient normally exists will produce the greatest net drag reduction. A disadvantage of this method is the need to develop small, compact yet reliable pumping elements to bring about the desired effects.

Suction would appear to be a most desirable method of drag reduction since it delays transition to turbulence and also tends to prevent separation, thus reducing the effect of pressure drag and providing substantial gains in performance. Figure A-3 indicates typical total drag reductions obtainable with suction devices. As with the other techniques involving transition delay, practical applications of suction to marine systems are developing slowly, but with promise for success in the near future.

(4) Gas-Filled Cavities: In conjunction with the previous technique of drag reduction, "blowing" or injection of fluid into the boundary layer has received considerable attention. Several variations to this method are possible, such as providing a special blower mechanism in the body which injects air, water, or a foreign gas into the surface layer through single or multiple slots, or taking the required energy directly from the free stream velocity, similar to the case of the slotted airfoil. In any application, the end result is the same; stabilization of the flow by building up the velocity profile next

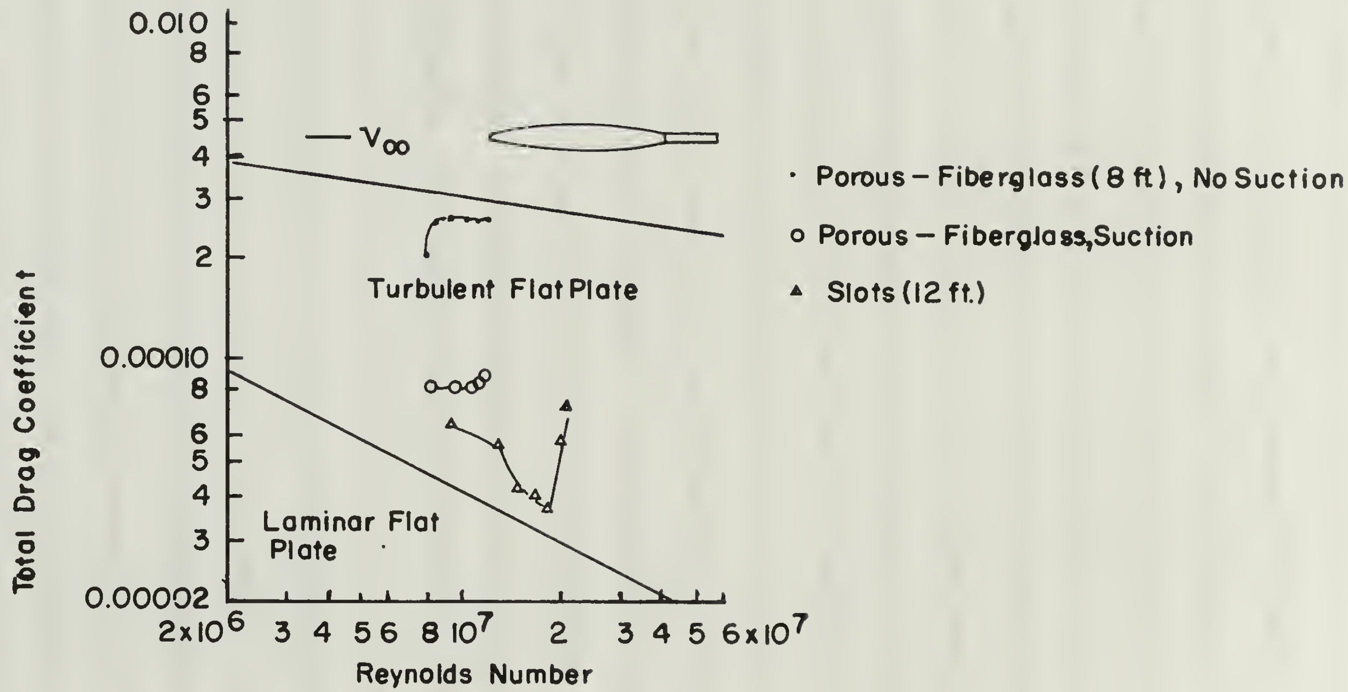

FIGURE A-3 RESULTS OF TESTS USING BOUNDARY LAYER SUCTION MODELS (REF. 87) to the wall; i.e., decreasing the value of the velocity gradient at the wall. This reduces the shear forces and drag losses and also prevents separation, thus reducing the pressure drag.

Particular efforts have been applied to the possibility of obtaining partial or complete enclosure of bodies in gas-filled cavities by air or foreign gas injection. Surface lubrication in which a gaseous layer is placed between the hull surface and the surrounding sea water would appear to hold great promise for considerable drag reduction. By producing a thin film on the surface through injection, chemical reaction, cavitation or various other processes, drag is decreased by shifting the momentum transport to the gas which has a lower viscosity rather than to the water.

A disadvantage of this technique is the need for development of a suitable mechanism for placing the gas cavity around the surface of the vehicle. This involves additional weight and volume and all such costs must be balanced against proposed reduction in drag to determine the feasibility of this method. This technique is limited to high speed, low range vehicles of relatively short lengths due to the weight and volume requirements and to the difficulties anticipated in generating stable gaseous layers over the entire surface of a large vehicle. As with suction, there is a possibility that the work required to pump the energy added to the surface layer will not be compensated for in terms of drag reduction.

(5) Heating and Cooling: Viscosity is a function of thermodynamic state of the fluid under discussion and, therefore, dependent to some degree on the temperature and pressure. This functional relationship is quite weak in the case of a liquid undergoing a pressure change

and very drastic pressure differences must exist before the viscosity is effected. Figure A-4 shows the considerably stronger relationship of viscosity of seawater to temperature.

The ordinary viscosity, μ, of water can be made to vary by heating or cooling the body surface, thus changing the results of the familiar drag relationship of the seawater viscosity and the velocity gradient. In a liquid medium, heating of the surface layer will cause a reduction in viscosity in the sublayer and an overall drag reduction results. The effect due to heating the fluid, in theory, stabilizes the laminar flow, but may cause other properties, such as density, to vary in an adverse manner. The exact nature of heating the sublayer, and the final results that might be expected, are unclear and presently, this technique is a long way from practical application.

Cooling of the boundary layer would increase the viscosity and provide a smaller Reynolds number for a given velocity and body length, thereby possibly delaying transition to turbulent flow and reducing drag. The overall effects of cooling have not been tested to any great extent, but it is believed that the complex nature of the mechanism involved would preclude its use in marine systems.

The second general category of frictional drag reduction techniques is referred to by some as the nonconventional method, but presently, there is more research into this aspect of the field than in the previous ones combined. The assumption is made that turbulent flow already exists in the boundary layer surrounding the body and efforts are centered on altering this turbulent flow by converting it to laminar if possible, or by decreasing the intensity of turbulence. The basic assumption of

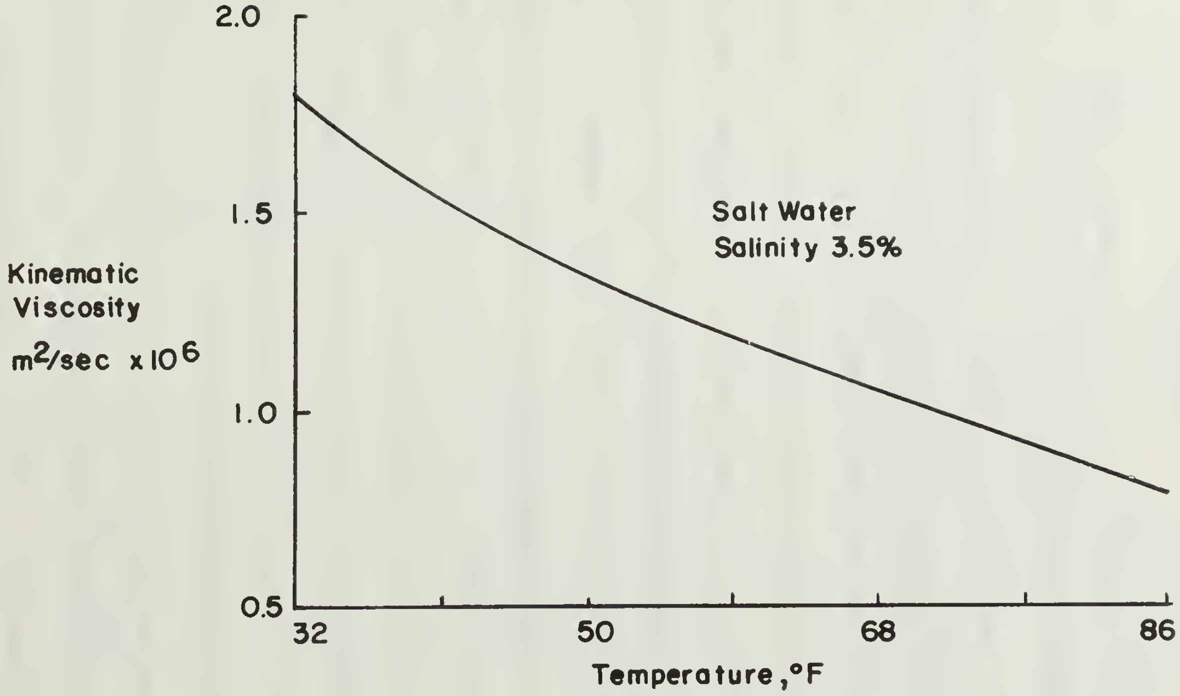

FIGURE A-4 EFFECT OF TEMPERATURE ON KINEMATIC VISCOSITY OF SEA WATER (REF. 87) violent disturbances in the surface layer seems logical following even a cursory examination of the various missions to be performed by useful marine systems.

The primary method belonging to this category is the injection of high molecular weight polymer materials into the fluid medium. The majority of the work being accomplished in the drag reduction field at the present time is concerned with the injection of so-called non-Newtonian fluids into the boundary layer surrounding a submerged body in order to modify the turbulent flow existing in this region. See references 86-89. A non-Newtonian fluid, in contrast to the definition of Newtonian fluids given previously would exhibit a nonlinear relation between the stress and strain rate, the exact nature of which is very complex. However, these additives are essentially Newtonian as measured by conventional instruments like the viscometer and it is considered that the use of the phrase "non-Newtonian additives" in this context is a misnomer.

Commercial applications have already been made of the principles involved in this means of drag reduction. In fact, it was the accidental discovery of reduced pressure drops and lower pumping power requirements in contaminated oil-field pipe flow that led to the intensive investigations being conducted today. Although the exact mechanism causing the drag reduction is still unknown, it has been shown that various materials of natural or synthetic substance, when added in extremely weak concentrations, to the turbulent layer around a submerged body, result in large drag reductions. See Figure A-5.

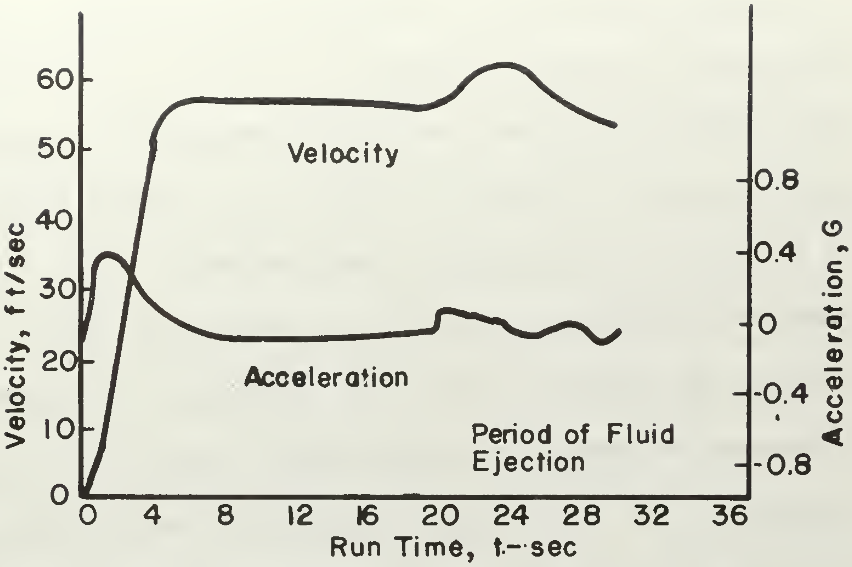

FIGURE A-5 RESULTS INDICATING VELOCITY AND ACCELERATION CHANGES WITH EJECTION OF HIGH-POLYMER SOLUTION (REF. 87)

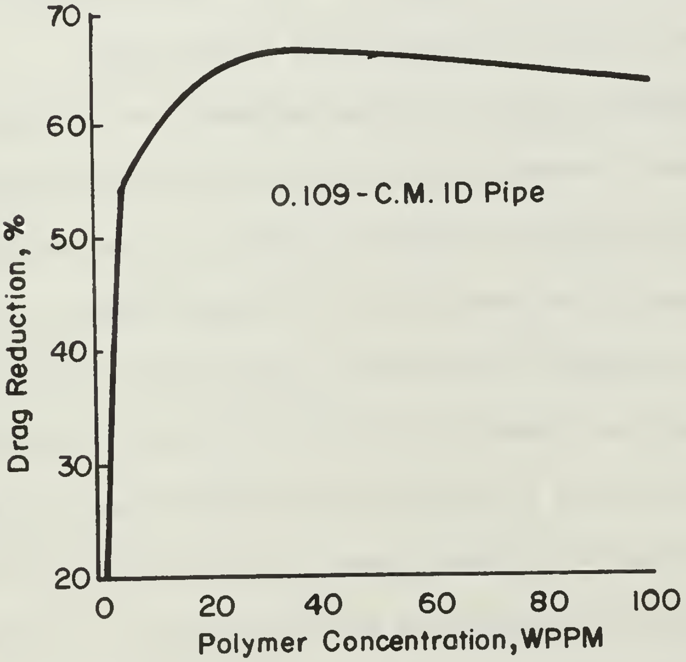

FIGURE A-6 DRAG REDUCTION IN PIPE FLOW WITH VARIOUS CONCENTRATIONS OF POLY (ETHYLENE OXIDE) (REF. 87)

Despite the lack of a theoretical formulation, some general rules can be stated concerning the selection of the types of materials and concentrations that have proved successful in numerous tests: (1) As shown by Figure A-6, there is an optimal concentration level of the material beyond which drag increases. (2) Three significant properties of polymer solutions or suspensions act to lower skin friction in turbulent flow, (a) linearity; i.e., threadlike appearance or essentially unbranched structure of "long chain" materials, (b) molecular weight, which must be high, but is not as critical or effective as the linearity factor, and (c) solubility, which is directly proportional to the resistance reduction effect. (3) Friction reduction in seawater is essentially the same as in fresh water. (4) Due to problems in mixing and dilution, it is desirable to form a slurry for practical applications and carry the substance in this configuration in the body.

Further tests are being conducted to determine the effects of additives, concentration rates, ejection techniques and velocities, optimal location of ejection ports, vehicle velocity and mixing techniques. The possibility of using a paint or coating-type application is under investigation. Small and reliable devices must be developed for injecting the additives into the boundary layer of the moving body and a reasonable cost must be maintained.

As indicated above, many facts are yet to be uncovered concerning the additive technique of drag reduction. It is theorized that since it is effective only when applied to turbulent flow, the drag reducing mechanism is primarily one of dampening or decreasing the intensity of turbulence in the flow. Supposedly, these polymers suppress turbulent fluctuations by a combination of the properties listed above.

Polymer injection would be most applicable for small, high speed craft with a burst requirement for emergency increase in speed. The need for surface smoothness and careful handling is eliminated in this case since there is no concern over maintaining laminar flow. The low concentrations required help to keep the costs down, but the non-recoverability of the additives may lead to a limit of burst or emergency operations. A big advantage of this method is the fact that it can be employed in weapons systems which conform to standard configurations. Disadvantages include cost and weight or volume requirements that must be deducted from available power plant spaces. At the present time this polymer injection technique appears to have the greatest potential for practical application to marine systems.

APPENDIX B

TABLE OF SYMBOLS AND ABBREVIATIONS

A	area
B	number of blades
b	span
C	relative velocity component
C_D	drag coefficient
C_L	lift coefficient
C_P	power coefficient
C_Q	torque coefficient
C_T	thrust coefficient
$C_T' = T/\frac{\rho}{2}V^2 \pi D \ell$	
$C_T'' = T/\frac{\rho}{2} V^2 \frac{\pi}{4} D^2$	
c	chord
c. s.	control surface
c. v.	control volume
D	diameter
Δ	increment in some quantity
F	tangential torque, force
f	frequency
g	gravitational constant
H	total pressure head
h	pressure head
I_{SP}	specific impulse
J_A	advance speed ratio = V/nD
$K = C_L b/\sin^2\phi \cos\gamma$	
K. E.	kinetic energy

k	reduced frequency
L	lift, wavelength
l	length
m	mass
m	massflow rate
N	pump rotative speed
N_s	pump specific speed
N_{ss}	pump suction specific speed
NPSH	net positive suction head, total pressure of flow at pump entrance
n	revolutions per unit time
$\hat{n}$	unit outward normal vector
P	total input power
$\mathbb{P}$	propulsion power
$\mathbb{P}_L$	exit loss
$\mathbb{P}_T$	thrust power
p	pressure
Q	volumetric flow rate, discharge rate, torque
$Q_C = Kr \sin(\phi + \gamma)$	
q	dynamic pressure
R	resultant force, radius of blade
r	radial coordinate, radius
S	area
T	thrust, temperature
$T_C = K \cos(\phi + \gamma)$	
t	time
U	tangential velocity vector

u	velocity, in the x-direction, relative exit velocity
V	velocity, rotor velocity
v	velocity in the y-direction

Greek Letters

α	angle of attack
α_r	augmentation ratios
α_1	ratio of propulsor thrust with rotation to that without rotation (psuedo-blade propulsor)
α_2	ratio of propulsor thrust to that of rotor alone (psuedo-blade propulsor)
$\alpha_3 = (2\ A_e/A_d)^{1/3}$	(ducted propeller augmentation ratio)
$\beta = (\alpha+\phi)$,	blade angle, angle that primary jet forms with reference axis
$\gamma = \tan^{-1} D/L$,	vorticity strength, ratio of specific heats
η	efficiency
η_{cy}	cycle efficiency
η_{ET}	energy transfer efficiency
η_P	ideal propulsive efficiency
η_o	overall efficiency
η_{th}	thermal efficiency
$\nu = V_\infty/V_e$,	effective speed ratio, kinematic viscosity
ρ	mass density
σ	cavitation number, area
σ_n	cavitation number based on rotational speed
σ_∞	cavitation number based on free stream velocity
$\phi = (\beta - \alpha)$,	angle resultant velocity vector forms with rotative velocity vector

τ	shear stress
θ	reference axis, cylindrical coordinate, blade orbit angle
ω	frequency of excitation, angular velocity
μ	viscosity
$\propto$	is proportional to

Subscripts

∞	total, free stream conditions
1	primary fluid
2	secondary fluid
0,1,2,....	station 0,1,2,...
a	ambient, aft, air, axial
b	blade
c	capture, cavitation, chamber
d	disk
e	exit conditions
exh	exhaust
f	forward, frontal, fuel
H_2O	water
i	initial, inlet, before interaction
j	jet, effective exhaust (velocity)
p	primary, spouting (velocity)
r	resultant
s	secondary, static
t	total
w	wake, wall

x	reference axis, abscissa
y	reference axis , ordinate
y = 0	at the wall
I	primary flow
II	secondary flow
I'	primary flow in absence of energy exchange with secondary flow (but same energy input as double flow system

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13. ABSTRACT

Increased interest on the part of the United States in the exploration and exploitation of the ocean environment has led to the assignment of diverse missions in this field to the military. Development of numerous vehicles and weapons systems and the propulsion units to propel them is required to accomplish these missions. In this paper, a general classification of propulsors is established and important performance parameters are defined. A variety of marine thrust devices is described and analyzed in detail, and a qualitative comparison of performance is made. General guidelines are offered for mating propulsors and vehicles for appropriate applications and particular mission requirements. The importance of drag reduction is recognized and various techniques are discussed in an appendix. Since this paper is intended to serve as a compendium on marine propulsors, an extensive bibliography has been incorporated.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Underwater Propulsion						
Marine Propulsion						
Water Screw						
Hydrodynamic Drag Reduction						
Performance Parameters						
Submersible						
Thrust Augmentation						
Waterjet						
Marine Propeller						
Condensuctor						
Cavitation						

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